IMPLEMENTATION OF A SINGLE IFFT BLOCK BASED PARTIAL TRANSMIT SEQUENCE TECHNIQUE FOR PAPR REDUCTION IN OFDM

A Thesis submitted in partial fulfillment of the Requirements for the degree of

Master of Technology
In
Electronics and Communication Engineering
Specialization: Communication and Signal Processing

By
ISHITA GUPTA
Roll No. : 211EC4102

Department of Electronics and Communication Engineering
National Institute of Technology Rourkela
Rourkela, Odisha, 769 008, India
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Under the Guidance of
Prof. Sarat K. Patra

Department of Electronics and Communication Engineering
National Institute of Technology Rourkela
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Dedicated to…

My late maternal grandmother,

My parents and my brother

DEPT. OF ELECTRONICS AND COMMUNICATION ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ROURKELA – 769008, ODISHA, INDIA

Certificate

This is to certify that the work in the thesis entitled **Implementation of a Single IFFT Block based Partial Transmit Sequence Technique for PAPR Reduction in OFDM** by **Ishita Gupta** is a record of an original research work carried out by her during 2012 - 2013 under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of Master of Technology in Electronics and Communication Engineering (Communication and Signal Processing), National Institute of Technology, Rourkela. Neither this thesis nor any part of it, to the best of my knowledge, has been submitted for any degree or diploma elsewhere.

Place: NIT Rourkela

Date: 21 May 2013

Dr. Sarat Kumar Patra

Professor

DEPT. OF ELECTRONICS AND COMMUNICATION ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ROURKELA – 769008, ODISHA, INDIA

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I certify that

a) The work contained in the thesis is original and has been done by myself under the general supervision of my supervisor.

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Ishita Gupta

21st May 2013

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ISHITA GUPTA

ishita.gupta1989@gmail.com

ABSTRACT

The current trends in wireless industry are based on multi-carrier transmission technique such as Orthogonal Frequency Division Multiplexing (OFDM) which is highly promising in terms of higher data rates and better immunity to frequency selective fading. Wireless standards like IEEE 802.11a/g/n, IEEE 802.16e and many others use one or other variation of OFDM, such as OFDMA and MIMO-OFDM. However OFDM is handicapped with a major problem of high peak-to-average power ratio (PAPR), which is a trait in-built to any multi-carrier transmission system. High PAPR causes non-linear distortion in the signal and hence results in inter-carrier interference and out-of-band radiation. To combat the effect of high PAPR, several PAPR reduction techniques have been devised over the last few decades. All these techniques have to strike a trade-off among some parameters such as computational complexity, PAPR reduction performance, BER performance and redundancy. Depending on the system in consideration, the most appropriate technique is hence selected. PTS technique has been in existence since 1997 and provides a very effective PAPR reduction technique with no limit on the maximum number of subcarriers. However the technique suffers from an acute problem of very high computational complexity. Hence a review of the literature shows that scholars and authors have tried to modify the technique so that the complexity is reduced significantly with or without a compromise of the PAPR reduction performance. This dissertation is extensively based on PTS technique and in this course limns a novel approach which offers better PAPR reduction and significantly reduces the algorithmic complexity with respect to the original technique. The multiple numbers of IFFT blocks has been replaced by a single block and the parallel processing has been replaced by serial processing. The exhaustive search for the optimum phase factors has been performed based on local minima rather than global

minima. The proposed technique has been simulated and the PAPR reduction performance of the new technique has been compared with that of original PTS to justify the claims of the technique. Similarly a comparison has been done among the complexities of the modified and the original techniques with the help of examples. Any signal processing algorithm is best judged for its performance when emulated on a DSP platform. The proposed technique has been emulated in a memory and power constrained environment on C6713DSK with TMS320C6713 processor using real signal input from Function Generator. The emulation results have been analyzed and it has been observed that the PAPR values obtained in emulation are at par with that of simulated values, hence establishing the feasibility of the technique to be implemented in Real-Time systems. Furthermore, to check the BER performance of the technique, the receiver has been simulated as well, based on the design proposed by the inventors of PTS. The transmitter receiver channel model has been simulated and the BER performance of OFDM system with Single IFFT block PTS has been compared with that of OFDM without any reduction technique. The results show that the PAPR reduction technique does not affect the BER performance of the underlying OFDM system. Hence a novel technique has been proposed to reduce the complexity of original PTS with betterment in PAPR reduction performance, negligible degradation in BER performance and feasibility for hardware implementation in real world system.

CONTENTS

NOMENCLATURE

c_{ki}	:	i^{th} information symbol at the k^{th} subcarrier
s_k	:	Waveform for k^{th} subcarrier
N	:	Number of sub-carriers
f_k	:	Frequency of k^{th} subcarrier
T_s	:	Symbol Period
$\Pi(t)$	:	Pulse shaping function (rectangular in this case)
c_k	:	Information bearing kth subcarrier
r_m	:	m^{th} received sample at every interval of T_s/N
c_k'	:	Demodulated k^{th} sample
S/P	:	Serial to Parallel Converter
P/S	:	Parallel to Serial Converter
D/A	:	Digital to Analog converter
LPF	:	Low Pass Filter
BPF	:	Band Pass Filter
A/D	:	Analog to Digital converter
X_n	:	Data symbols to be mapped to n^{th} sub-carrier
Δf	:	Subcarrier spacing
T	:	Period for pulse-shaping symbol
L	:	Oversampling factor
M	:	Number of sub-blocks in PTS
W	:	Number of allowed phase factors
b_w	:	w^{th} allowed phase factor
θ_w	:	Phase value of w^{th} allowed phase factor

$\mathbf{X}_m$	:	m^{th} sub-block
$\boldsymbol{x}_m$	:	m^{th} PTS
$b^{(m)}$	:	Phase factor for the m^{th} PTS
$\tilde{\boldsymbol{x}}$	:	Modified OFDM symbol formed by combination of phase rotated PTSs
C	:	Number of candidate signals
$\tilde{\boldsymbol{x}}_{opt}$	:	Optimum OFDM symbol with minimum PAPR value
$\hat{\boldsymbol{x}}_m$	:	Partial OFDM symbol formed in Single IFFT block PTS after the $(m+2)^{th}$ iteration
t_{ifft}	:	Time taken for one N-point IFFT computation
t_{add}	:	Time taken for one N-point vector addition
t_{phase}	:	Time taken for one Phase rotation`
t_{PAPR}	:	Time taken for PAPR computation of one N-point symbol
t_{cmpr}	:	Time taken for one PAPR comparison
t_{sym}	:	Time taken for generation of one OFDM symbol in original PTS
t_{pts}	:	Time taken for generation of the optimum OFDM symbol in original PTS
t_{part}	:	Time required for a partial OFDM symbol to be formed with the minimum possible PAPR for that particular combination of PTSs
$t_{single\_ifft\_pts}$	:	Total time required for generating an OFDM symbol using Single IFFT block PTS
$t_{pipelined\_case1}$	:	Time required for OFDM symbol generation in case 1 of pipelining
$t_{pipelined\_case2}$	:	Time required for OFDM symbol generation in case 2 of pipelining
t_{2nd_loop}	:	Time required for completion of the second loop for one PTS in Single IFFT block PTS
$\tilde{\boldsymbol{x}}_m$	:	Phase rotated m^{th} PTS
$\tilde{y}$	:	Data received after performing FFT of $\tilde{\boldsymbol{x}}$

ABBREVIATIONS

IP	:	Internet Protocol
OFDM	:	Orthogonal Frequency Division Multiplexing
VLSI	:	Very Large Scale Integration
CMOS	:	Complementary Metal Oxide Semiconductor
DAB	:	Digital Audio Broadcasting
WLAN	:	Wireless Local Area Network
WiMAX	:	Worldwide Interoperability for Microwave Access
LTE	:	Long Term Evolution
PAPR	:	Peak to Average Power Ratio
ISI	:	Inter-symbol Interference
IDFT	:	Inverse Discrete Fourier Transform
DFT	:	Discrete Fourier Transform
IFFT	:	Inverse Fast Fourier Transform
FFT	:	Fast Fourier Transform
DAC	:	Digital to Analog Converter
RF	:	Radio Frequency
IQ	:	In-phase and Quadrature
ADC	:	Analog to Digital Converter
DVB	:	Digital Video Broadcasting
MIMO	:	Multiple Input Multiple Output
PAN	:	Personal Area Network
OFDMA	:	Orthogonal Frequency Division Multiple Access
SC-FDMA	:	Single Carrier Frequency Division Multiple Access

MC	:	Multi-carrier
CCDF	:	Complementary Cumulative Distribution Function
PA	:	Power Amplifier
PTS	:	Partial Transmit Sequence
DSP	:	Digital Signal Processor
BER	:	Bit Error Rate
BPSK	:	Binary Phase Shift Keying
QPSK	:	Quadrature Phase Shift Keying
CPU	:	Central Processing Unit
GB	:	Gigabytes
RAM	:	Random Access Memory
GHz	:	Giga Hertz
dB	:	Decibel
DSK	:	Digital Signal Processor Starter Kit
JTAG	:	Joint Test Action Group
USB	:	Universal Serial Bus
LED	:	Light Emitting Diodes
TI	:	Texas Instruments
MHz	:	Mega Hertz
MIPs	:	Million Instructions per Second
MFLOPs	:	Mega Floating-Point Operations Per Second
SDRAM	:	Synchronous dynamic random access memory
KHZ	:	Kilo Hertz
CCS	:	Code Composer Studio
DSO	:	Digital Storage Oscilloscope

AWGN	:	Additive white Gaussian noise
SNR	:	Signal to Noise Ratio
SER	:	Symbol Error Rate
MCCDMA	:	Multicarrier Code Division Multiple Access
BTS	:	Base Transmit Station
FPGA	:	Field Programmable Gate Array

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1

PEAK TO AVERAGE POWER RATIO IN OFDM: AN INTRODUCTION

The wireless communication industry has been continuously evolving from analog to digital, circuit switched to IP-centric platforms and from narrowband to broadband [1]. The single carrier transmission system used extensively in 2nd generation mobile communication system was bottlenecked by the limitation of bandwidth and data-rates. The bandwidth of the system is required to be less than the coherent bandwidth of the channel and hence an upper limit is imposed on the data-rates possible. The concept of multi-carrier transmission evolved consequently.

The most significant and widely used multi-carrier transmission system is Orthogonal Frequency Division Multiplexing (OFDM). The concept of OFDM was introduced by R.W. Chang in 1966 and was patented in 1970. However the usage of OFDM was limited to military communication due to the lack of broadband application and powerful integrated electronic circuits to support the required complex computation. In 1990 the arrival of broadband digital applications and tremendous growth in VLSI design and process technology brought OFDM into limelight [2]. The first commercial OFDM based wireless system came up in 1995 in the form of Digital Audio Broadcasting (DAB) standards [1]. The development in the field of OFDM continued in parallel to all other simultaneously existing technologies until the major 21st century wireless standards like WLAN, WiMAX and LTE started using OFDM in one way or the other.

The first couple of sections describe the basic principle of OFDM along with the transmitter and receiver models used in practical purposes. The advantages and disadvantages of OFDM are discussed in following sections. The concept of peak-to-average power ratio in OFDM is discussed along with the adverse effects of high PAPR values in OFDM transmission system. This chapter has been concluded by motivation and objective to the research work conducted.

1.1 Introduction to OFDM

The principle of multi-carrier transmission is to divide the entire bandwidth into smaller bandwidths each with a different sub-carrier frequency, such that each of these narrow-band signals is immune to frequency selective fading and the data-rates are improved in comparison to single-carrier system as the total bandwidth can be increased significantly. The system has been illustrated in the following figure:

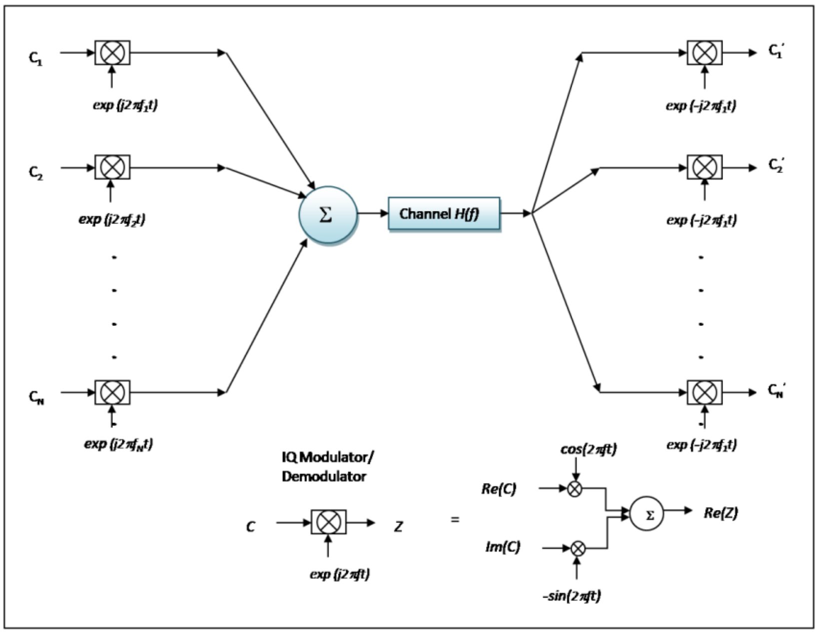


FIGURE 1-1: CONCEPTUAL DIAGRAM FOR GENERIC MULTI-CARRIER TRANSMITTER-RECEIVER SYSTEM

The multi-carrier modulated signal can hence be expressed mathematically as [2]:

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{k=1}^{N} c_{ki} s_k(t - iT_s) \tag{1}$$

$$s_k(t) = \Pi(t) e^{j2\pi f_k t} \tag{2}$$

$$\Pi(t) = \begin{cases} 1, & 0 < t \leq T_s \\ 0, & t \leq 0, t > T_s \end{cases} \tag{3}$$

where,

c_{ki}	=	ith information symbol at the kth subcarrier
s_k	=	Waveform for kth subcarrier
N	=	Number of sub-carriers
f_k	=	Frequency of kth subcarrier
T_s	=	Symbol Period
$\Pi(t)$	=	Pulse shaping function (rectangular in this case)

The optimum detector for each sub-carrier would use a filter matching the sub-carrier waveform or a correlator matched to the sub-carrier. Thus using such a detector, the detected information symbol $c_{ki}{}'$at the output of the correlator is [2]:

$$c_{ki}{}' = \frac{1}{T_s} \int_0^{T_s} r(t - iT_s)\, s_k{}^* dt \tag{4}$$

$$c_{ki}{}' = \frac{1}{T_s} \int_0^{T_s} r(t - iT_s)\, e^{-j2\pi f_k t} dt \tag{5}$$

where $r(t)$ is the received time domain signal. The correlation between two sub-carriers can be evaluated as following [2]:

$$\delta_{kl} = \frac{1}{T_s} \int_0^{T_s} s_k\, s_l{}^* dt \tag{6}$$

Hence,

$$\delta_{kl} = \frac{1}{T_s}\int_0^{T_s} e^{j2\pi f_k t}\, e^{-j2\pi f_l t} dt$$

$$\delta_{kl} = \exp(j\pi(f_k - f_l)T_s)\frac{\sin\{\pi(f_k - f_l)T_s\}}{\pi(f_k - f_l)T_s} \quad (7)$$

If $f_k - f_l = m.\frac{1}{T_s}$ where |m| = 0,1,2,.. then $\delta_{kl} = 0$.

Therefore s_k and s_l will be orthogonal to each other. The spectrum of the sub-carriers may overlap but yet can be detected using matched filters with no inter-symbol interference (ISI). This increases spectral efficiency as there is no wastage in bandwidth required to separate two adjacent sub-carriers. Difference in frequency between these sub-carriers will be integral multiples of inverse of symbol time. Such a multi-carrier modulation system is effectively termed as orthogonal frequency division multiplexing.

The various advantages as well as drawbacks of OFDM have been discussed in the following sections [1], [2].

1.1.1 Advantages of OFDM

- ***High Spectral Efficiency***: Due to the orthogonality of the sub-carriers in OFDM, there is no requirement for guard bands between two adjacent sub-carriers to check for inter-symbol interference. So the spectral efficiency is very high for OFDM. The complete spectrum is very effectively used as the spectra of adjacent sub-carriers are overlapped. An example of OFDM spectrum is shown in the figure.

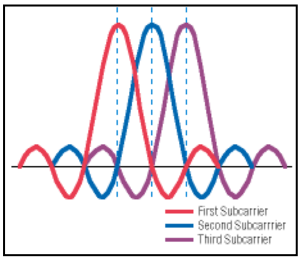


FIGURE 1-2: OFDM SPECTRUM

- ***Resistance to Frequency Selective Fading***: The complete bandwidth used by an OFDM symbol is generally more than the coherent bandwidth of the channel. This can result in frequency selective fading of the signal. However since OFDM symbol is made up of multiple sub-carriers with narrow-band spectra, each of this sub-carrier can overcome the effect of frequency selective fading and hence the symbol is immune to such channel effects. This makes OFDM very robust against channel dispersion.
- ***Ease of phase and channel estimation***: In a time-varying environment, the estimation of phase and channel parameters is tough. But in case of OFDM, due to the orthogonality of the sub-carriers, this process of estimation is aided by the information already carried by the sub-carriers.
- ***Ease of VLSI Implementation***: Due to the use of blocks like IFFT/FFT, it is easier to implement OFDM transmission and reception system in VLSI. This allows higher number of sub-carriers to be used without much significant increase in hardware requirement and hence effectively improves the data-rate and spectral efficiency.

1.1.2 Disadvantages of OFDM

In spite of multiple and significant advantages, OFDM suffers from some major drawbacks which needs to be handle with extra importance in case of OFDM transmission and reception. The disadvantages or drawbacks are as discussed below [1], [2]

- ***High PAPR value***: The peak-to-average power ratio of an OFDM signal is generally very high as OFDM signal is addition of a large number of sub-carriers. When the number of sub-carriers is high, the value of PAPR tends to overshoot and hence causes multiple problems which are discussed in details in Section1.4.3.
- ***Sensitivity to Frequency and Phase Offset***: As the sub-carriers are very closely spaced, OFDM signal is very sensitive to errors in frequency values. This, in turn, results in

frequency offset errors as well as phase offset errors. Very fine tuning is required to take care of the phase and frequency offsets.

- ***Inter-carrier Interference***: The property of orthogonality is sometimes violated by the sub-carriers in real world transmission and due to the loss of orthogonality, inter-carrier interference occurs. This causes distortion in the signal as well as loss of information.

1.2 OFDM Transceiver

The basic principle of OFDM transmission involves a large number of sub-carriers. The more the number of sub-carriers the better will be the immunity to the frequency selective fading of signals and similarly higher will be the data-rates. However to realize this in hardware will lead to a complex architecture with huge number of oscillators and filters.

This problem was handled by Weinstein and Ebert who gave the concepts of implementing OFDM modulation by IDFT and demodulation by DFT [2]. Considering only one OFDM symbol, if s(t) is sampled at every interval of T_s/N then the mth sample of s(t) is obtained as[2]:

$$s_m = \sum_{k=1}^{N} c_k e^{j2\pi f_k \frac{(m-1)}{N} T_s} \tag{8}$$

By the condition of orthogonality, $f_k - f_l$= m.$\frac{1}{T_s}$. Denoting $f_k = \frac{(k-1)}{T_s}$,

$$s_m = \sum_{k=1}^{N} c_k e^{j2\pi f_k \frac{(m-1)(k-1)}{N}} \tag{9}$$

Thus it can be concluded from equation (9)that at the transmitter end,

$$s_m = IDFT\{c_k\}, \qquad m = 1,2..,N \tag{10}$$

And similarly at the receiver end, if r_m is the received sample at every interval of T_s/N and $c_k{}'$ is the demodulated kth sample, then:

$$c_k' = DFT\{r_m\}, \qquad k = 1,2,..,N \tag{11}$$

The implementation of OFDM transmission and reception using DFT and IDFT would however have very high complexity as DFT involves N^2 complex multiplications. Thus as the number of sub-carriers is increased, the complexity will increase exponentially. This problem has been addressed to by the implementation of OFDM transmission and reception using fast-Fourier-transform-algorithms. Thus OFDM transmission is implemented by an IFFT block and reception by a FFT block. This was aided by the improved VLSI implementation of various fast algorithms of FFT/IFFT. The number of sub-carriers could thus be increased without much increase in hardware requirement.

1.2.1 OFDM Transmitter

The incoming serial data stream is converted to parallel blocks of data, with the number of elements in one parallel block being equal to the number of sub-carriers, say N. The parallel block of data is then passed through an N-point IFFT block to obtain the OFDM symbol. Thus the OFDM symbol is in digital time domain. Guard time is introduced between two successive OFDM symbols in the form of cyclic prefix to prevent ISI due to channel dispersion. The digital data is then converted to real time waveform using digital-to-analog converter (DAC). Baseband signal is up-converted to appropriate RF pass-band with IQ mixer or modulator. The transmitter is illustrated in the following figure.

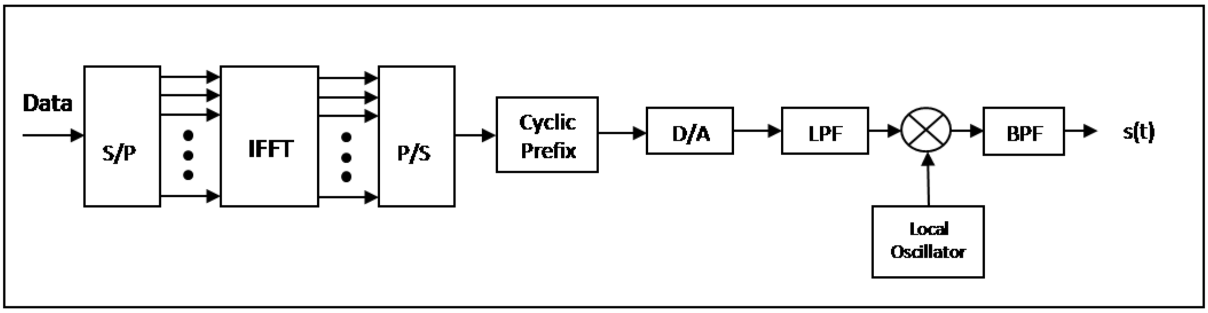


FIGURE 1-3: OFDM TRANSMITTER USING IFFT

S/P : Serial to Parallel Converter

P/S : Parallel to Serial Converter

D/A : Digital to Analog converter

LPF : Low Pass Filter

BPF : Band Pass Filter

1.2.2 OFDM Receiver

OFDM signal is down-converted to baseband with an IQ demodulator. The analog signal is sampled and quantized using an ADC. Demodulation is done by performing DFT. Baseband signal processing is done to recover the data. The receiver is illustrated in the following figure:

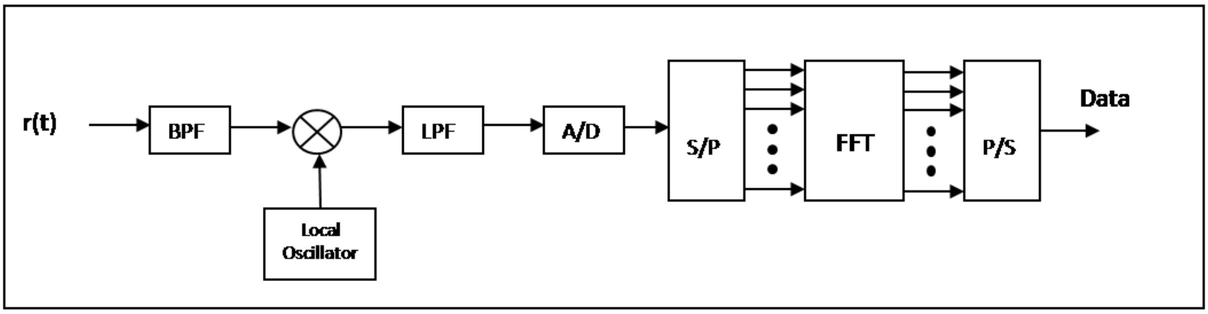


FIGURE 1-4: OFDM RECEIVER USING FFT

1.3 Applications of OFDM

The first commercial OFDM based system was Digital Audio Broadcasting (DAB) standards developed in 1995. Henceforth, OFDM has been adopted as the technology for some of the most promising standards of wireless industry [1], [2] and [3]

Immediately following the development of DAB standards, the European Digital Video Broadcasting (DVB) standards came up which utilized OFDM as the main technology. Following these standards, OFDM was taken up as the technology for wireless LAN (Wi-Fi) with the protocol IEEE 802.11a being established. It was then followed by IEEE

802.11g WLAN which also used OFDM. Currently the most used protocol IEEE 802.11n uses OFDM as the base technology.

The IEEE 802.16 standard commonly known as WiMAX uses OFDM coupled with MIMO system. Similarly standards like IEEE 802.15.3a, also known as wireless PAN uses a modified version of OFDM.

The 4th generation mobile industry also started using OFDM as LTE was introduced after 3rd generation mobile communication standards was established. The 3GPP standards were developed using OFDMA along with SC-FDMA and MIMO system. OFDMA is a variation of OFDM where in place of multiplexing signals, users are provided access in a multiplexed manner. Hence the current wireless and mobile industry is extensively based upon OFDM and its variants.

1.4 Peak to Average Power Ratio in OFDM

Any multi-carrier signal is the summation of a large number of independent or orthogonal signals. Hence the envelope of the MC signal may vary extensively. This variation is quantified by the ratio of the peak value to the average value of the MC signal and is termed as peak-to-average-power-ratio (PAPR) [4]. PAPR is an important factor to be considered about OFDM, as high values of PAPR has certain demerits.

1.4.1 Introduction to PAPR [4]

Let the data symbols be X_n where n ranges from 0 to N-1. N is the number of sub-carriers for the OFDM system. So let the parallel block of data required before OFDM generation is

$$\boldsymbol{X} = [\boldsymbol{X}_0, \boldsymbol{X}_1, \dots, \boldsymbol{X}_{N-1}] \tag{12}$$

So the complex baseband representation of an OFDM signal with N sub-carriers is:

$$x(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{j2\pi n\Delta f t} \qquad ,0 \leq t < NT \tag{13}$$

where Δf is the subcarrier spacing and T is the period for pulse-shaping symbol.

For this signal, the PAPR can be defined as follows:

$$PAPR = \frac{\max\limits_{0 \leq t < NT} |x(t)|^2}{\frac{1}{NT}\int_0^{NT} |x(t)|^2\, dt} \tag{14}$$

However equation (14) gives PAPR for an analog signal. To obtain PAPR for a digital OFDM signal, let us assume that only NL equidistant samples of x(t) will be considered where L is an integer and is greater than 1. The samples of the signal can thus be represented as:

$$\boldsymbol{x} = [x_0, x_1, \dots, x_{N-1}] \tag{15}$$

Thus the OFDM signal can be represented in digital domain as:

$$x_k = x\left(\frac{k.T}{L}\right) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{\frac{j2\pi k\Delta f nT}{L}}, k = 0,1, \dots, N-1 \tag{16}$$

The PAPR of the signal described by the equation (16) is given by:

$$PAPR = \frac{\max\limits_{0 \leq k < NL-1} |x_k|^2}{E[|x_k|^2]} \tag{17}$$

1.4.2 CCDF for PAPR

The most common and frequently used performance measure for PAPR reduction techniques is termed as Complementary Cumulative Distribution Function (CCDF) [4]. CCDF denotes the probability that the PAPR of a data-block exceeds a given threshold. If the CCDF graph is plotted against the threshold values, the more vertical the graph is, the better is the PAPR reduction performance [4].

1.4.3 High values of PAPR: Associated problems

The value of the PAPR describes the variation of power level of the OFDM signal to be transmitted. If the PAPR value is very high, the power amplifier (PA) in the transmitter may get saturated due to transmission of very high power [4]. Once saturated, the PA will operate in non-linear region. Non-linear operation of PA will result in generation of unwanted frequencies by non-linear modulation of the incoming signal. Hence the following unwanted events may occur [4], [5]:

- Inter-modulation of carriers
- Out-of-band radiation due to spectral leakage

1.4.4 Eliminating distortion due to high PAPR

The effect of high PAPR on the PA can be handled in a multiple number of methods which are described along with their pros and cons as below:

- The peak transmit power may be limited by either regulatory or application constraints to reduce the average power allowed under multi-carrier transmission [4]. However this technique reduces the range of multi-carrier transmission and obstructs one of the major advantages of OFDM to be used.
- The dynamic range of the power amplifier can be increased to accommodate the maximum power to be transmitted [4]. But this technique is expensive as PAs with higher dynamic range comes at a greater cost. Again this requires hard-coding of the maximum allowed power which in turn limits the range of OFDM.
- The most feasible method yet improvised, is to use number of techniques that reduce the PAPR of the generated OFDM signal to an acceptable limit before being transmitted. These techniques require an extra set of computation but allow the OFDM range to expand as required and also do not add on to the overall cost of the transmitter as the processing can be done in baseband.

1.5 PAPR Reduction Techniques

A large number of PAPR reduction techniques have been proposed over a long period during the development of OFDM technology. The main objective of these techniques is to reduce the PAPR of the OFDM signal to an acceptable value before the OFDM signal is sent to the transmitter. The different techniques are listed below [4]:

- Amplitude Clipping and Filtering
- Coding
- Partial Transmit Sequence Technique
- Selected Mapping Technique
- Interleaving Technique
- Tone Reservation Technique
- Tone Injection Technique
- Active constellation extension technique
- Clustered OFDM
- Two-dimensional pilot symbol assisted modulation [used in coherent OFDM for channel estimation]

1.5.1 Criteria for selection of PAPR Reduction Techniques

There are a number of parameters or factors which are considered about the PAPR reduction techniques [4]. Not all the criteria can be fully satisfied by any of the existing PAPR reduction techniques. A tradeoff is required between these factors to select the most appropriate technique depending on the system under consideration.

The factors are as listed below:

1. ***PAPR Reduction capability***: The PAPR reduction capability is described by the reduction of PAPR value (in dB) after the technique is applied to OFDM transmission system. It is measured by CCDF graph.
2. ***Power Increase in transmit signal***: The technique must not increment the total power level that is being transmitted. If it does happen, the increment in power has to be within a permissible limit.
3. ***BER increase at the receiver***: The technique must not introduce unwanted errors into the transmitted bit stream, such that the overall BER at the receiver is increased. In other words the technique must not distort the signal.
4. ***Loss in data rate***: The technique may use some extra bits and this may result in a loss of data rate. The loss is acceptable up to certain value dependent on the system under consideration
5. ***Computational complexity***: The technique may satisfy all the other criteria but at the cost of a very high computational complexity. If this complexity is exceedingly high, the technique might not be suitable for hardware implementation as it will incur higher cost, power and time which are not desirable in speedy networks based on OFDM.

The following Table 1-1 presents the comparison of all these techniques based on the criteria presented earlier [4].

TABLE 1-1: COMPARISON OF PAPR REDUCTION TECHNIQUES

Technique name	Power increase	Distortion-less	Loss in data rate	Computational Complexity
Amplitude clipping & filtering	No	No	No	Low
Coding	No	Yes	Yes	Medium
Partial Transmit Sequence	No	Yes	Yes	Very High
Selected Mapping	No	Yes	Yes	High
Interleaving	No	Yes	Yes	Medium
Tone Reservation	Yes	Yes	Yes	Medium
Tone Injection	Yes	Yes	No	Medium
Active constellation extension	Yes	Yes	No	Medium

The Partial Transmit Sequence technique has a very high computational complexity but delivers a remarkably good performance in terms of PAPR reduction. The higher the complexity of the technique and the more extensive the technique is, better is the PAPR reduction performance [4]. Hence this technique has been worked upon by a number of researchers with an objective to reduce the computational complexity so as to avail the PAPR reduction performance in an efficient manner.

1.6 Motivation

The advent of 4th generation wireless communication technology has been possible due to the OFDM technology. The current world requires speed and efficient bandwidth utilization, which is very well provided by OFDM. However implementation of OFDM has the major concern of high PAPR like any multi-carrier signal. For the last few decades, researchers have been trying to device techniques that might reduce the PAPR value to an acceptable limit without causing unwanted distortions or loss in data rates or added complexity. Some techniques provide good PAPR reduction but have very high computational complexity while some techniques have a lower complexity but introduce some distortion in the signal. There is a trade-off among various such factors and hence global optimization is required to hit equilibrium and choose the most suited technique.

The PTS technique has been among those techniques which presents a remarkable PAPR reduction performance but is handicapped by a very high computational complexity as well as loss of data rates. Thus this technique has been the interest of researchers to develop upon such that the PAPR reduction capability can be exploited yet the high complexity and the loss of data rates can be overcome efficiently. Care has been exercised to preserve the advantages of the technique while the disadvantages have been eradicated to a concordant degree. Motivation has been derived from such research works for the betterment of the technique and to address the drawbacks in a novel approach. The concepts of parallel and serial system have been used in the work. It is known that serial system has a lower complexity in comparison to parallel system at a cost of throughput time. The design of the new technique has been improvised on the basis of this concept.

Any signal processing algorithm is best tested on a DSP platform to establish the hardware feasibility as well as ability for real time operation of the technique. Motivation has been derived from this principle to implement the proposed technique on DSP platform using real signals generated from function generator.

1.7 Objective of the Work

The main objective of this work is to modify an existing PAPR reduction technique termed as PTS Technique such that the computational complexity of the technique is reduced. Higher computational complexity demands more time, power and hardware resources thus increasing the cost as well. By reducing the complexity of the technique and yet delivering a performance equal to or better than the existing technique, the power, hardware requirement and cost can be optimized.

To realize the objective, the following analysis and investigations were required to be undertaken:

- Study and analyze the existing PTS technique and understand the main reasons behind the high computational complexity of the technique.
- Device a new method that would preserve the principle of the technique, yet reduce the complexity to a much lower value. The algorithm for this method has to be developed and simulated to test if the PAPR reduction performance is maintained or not.
- Implement the newly devised algorithm in hardware such as DSP processor to test the design feasibility, hardware realization and performance analysis of the algorithm in real-time.

1.8 Thesis Organization

The thesis has been organized into five chapters. The current chapter gives the introduction to the OFDM technology and discusses the importance of peak-to-average power ratio. Furthermore it describes the different PAPR reduction techniques in brief and compares them based on different performance metrics. The motivation and the objective have been discussed in the penultimate sections while the last section describes the complete thesis organization.

Chapter 2: The second chapter describes the original Partial Transmit Sequence technique for PAPR reduction and discusses the merits and demerits of the same.

Chapter 3: The third chapter describes the proposed Single IFFT block PTS technique and illustrates the performance of the same in comparison to the original PTS. Simulation results and an analysis of the drawback of the technique have been included in the later sections of the chapter. The receiver of the Single IFFT block PTS has been designed and the simulation for a complete transmitter-channel-receiver model has also been done. The third chapter describes the complete design and the simulation results. An error rate performance has been analyzed and compared with that of OFDM without any PAPR reduction technique.

Chapter 4: The fourth chapter discusses the hardware implementation of the technique using TMS320C6713DSK. The various results obtained have been included in the different sections of the chapter.

Chapter 5: The fifth chapter presents the conclusion to the complete work and talks about the scope of future work to the research work that has been presented in the thesis.

2

Partial Transmit Sequence Technique for PAPR Reduction

The demerits of high PAPR incurred in OFDM system is generally addressed to by a number of PAPR reduction techniques which reduce the PAPR value to a certain threshold such that the derogatory effects are eliminated [4]. Some of the techniques have moderate PAPR reduction capability but have lower complexity while some have very good PAPR reduction capability at the cost of very high complexity. Partial Transmit Sequence technique complies with the second type of techniques with high computational complexity and good PAPR reduction performance. The existing PTS technique has been described in the chapter aided by mathematical equations and block diagrams.

The chapter also discusses the advantages of this technique and points out the merits of using PTS technique in comparison to other techniques. The later sections describe about the limitations of the technique, which provide the feed to the complete research work. Since the technique has been invented, several modifications have been done by different researchers to eradicate completely or to certain level, the limitations of the technique. The last section provides the literature review that has been conducted to study a number of modified PTS implementations.

2.1 Partial Transmit Sequence Technique

The PTS technique was first proposed by Müller and Huber in 1997 [5], [6] as a modification to the existing Selective Mapping technique. The principle of the technique can be quoted as:

"***The coordination of appropriately phase rotated signal parts to minimize the peak power of the multiplex signal***"

2.1.1 PTS Technique: Algorithm

The complete algorithm as proposed by the authors is described below [5]. Figure 2-1 illustrates a single iteration in the form of a block diagram.

- The incoming bit stream is converted to a parallel block of data, as required in normal OFDM transmission that is described in Chapter 1.
- The parallel block of data is then divided into smaller sub-blocks. Each of these sub-blocks has the same length as the original parallel block of data. As for example if there are N sub-carriers, then the length of the parallel block of data will be N. Similarly the length of each sub-block will also be N. However not all the N elements of a sub-block will be non-zero. The division will be such that, some of the sub-carriers have non-zero values in a sub-block while others have zero. And it is to be noted that a set of sub-carriers cannot have non-zero values in more than one sub-block. In this way, effectively the addition of all sub-blocks will give the original parallel block of data as the sum.
- The sub-blocks are then simultaneously passed through IFFT blocks which perform the inverse Fourier transform of each of these sub-blocks. The output of each of these IFFT blocks is referred to as **partial transmit sequence**.
- Each of the PTSs is then simultaneously rotated by a certain pre-defined phase factor. The phase factor is selected from a set of allowed values which is defined

earlier. Once rotation is complete, the phase-rotated PTSs are added up to get a **candidate signal**.

- The entire process is then again performed but with a different combination of phase factors being multiplied with the PTSs. This is continued until all possible combinations of phase-factor and PTS has been generated. Thus a large number of candidate signals are generated.
- The candidate signals are compared on the basis of their PAPR value and the one with the lowest PAPR is chosen as the correct OFDM symbol to be transmitted.

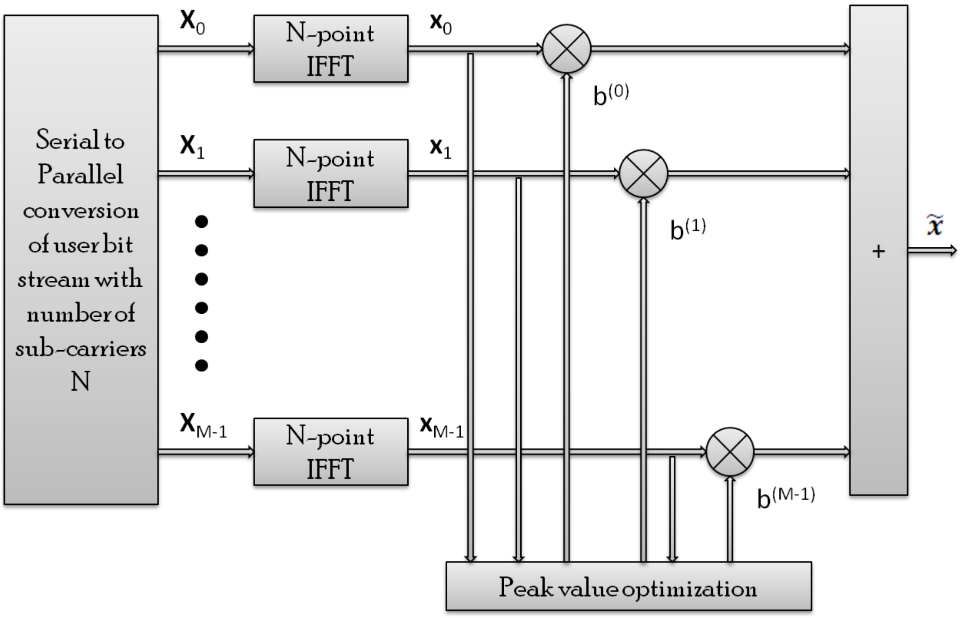
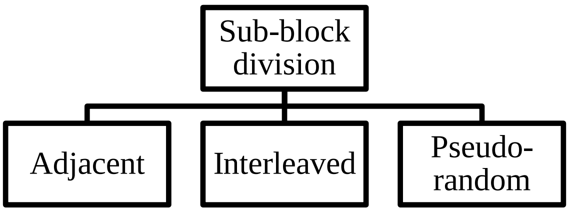


FIGURE 2-1: BLOCK DIAGRAM OF PARTIAL TRANSMIT SEQUENCE TECHNIQUE

It has been pointed out by the authors that there may not be any hard and fast rule to divide the incoming parallel block of data into sub-block. However to make the process convenient and streamlined three types of sub-block division have been proposed by the authors [5]. All of these sub-block division schemes assign equal number of non-zero sub-carriers to each sub-block. It has been proved mathematically by Müller and Huber in their paper that, the more random the distribution of sub-carriers is, the lesser the correlation that exists among the sub-blocks and hence the better is the PAPR reduction performance [5].



1. Adjacent Sub-block division: If the number of sub-carriers N is a multiple of the number of sub-blocks M, then the first N/M sub-carriers are assigned to the first sub-block. Similarly the second sub-block will have non-zero values for the next set of N/M sub-carriers. In this case, the correlation among the sub-blocks is very high. The scheme can be represented with an example in the Figure 2-2:

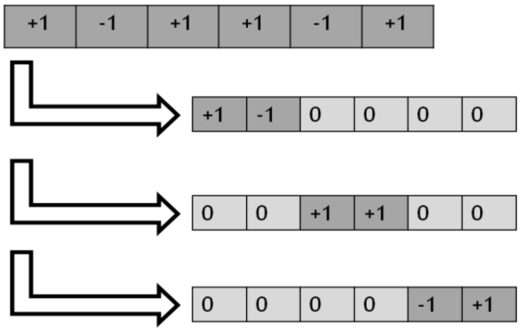


FIGURE 2-2: ADJACENT SUB-BLOCK DIVISION

2. Interleaved Sub-block division: In this scheme, alternate or sub-carriers after a certain fixed interval are assigned to a sub-block. As for example, the first sub-block might be assigned every 3rd sub-carrier and so on. This scheme is more random than adjacent type, but still certain level of correlation exists among the sub-blocks due to a fixed pattern being observed. Figure 2-3 illustrates the scheme with an example.

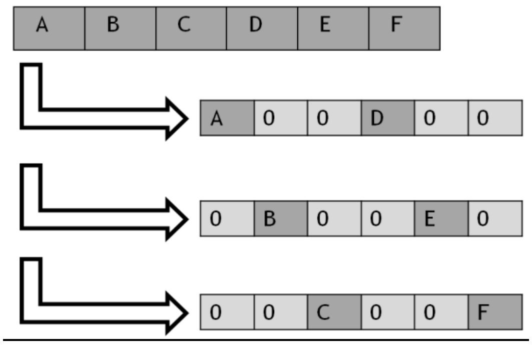


FIGURE 2-3: INTERLEAVED SUB-BLOCK DIVISION

3. Pseudo-random Sub-block division: This scheme gives the least correlation among the sub-blocks as the sub-carriers are assigned in an almost random method. It is termed as pseudo-random as certain amount of certainty exists in the assignment of sub-carriers to make the process streamlined. This is the best way of sub-block partition. Figure 2-4 illustrates the scheme in the form of an example.

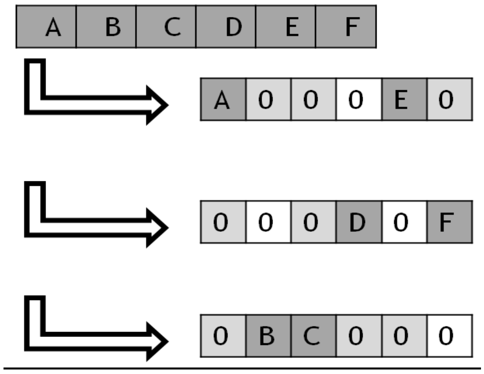


FIGURE 2-4: PSEUDO-RANDOM SUB-BLOCK DIVISION

2.1.2 PTS Technique: Mathematical analysis

Let the incoming serial stream of data be represented as X. If the number of sub-carriers be N, then let the parallel block of data obtained after serial to parallel conversion be represented as:

$$\boldsymbol{X} = [X_0, X_1, \dots, X_{N-1}]$$

If the number of sub-blocks be M, then for convenience let us assume that $\lfloor N/M \rfloor$ elements in each sub-block will be non-zero. T. So the sub-blocks can be expressed as $\mathbf{X}_m$ where:

$$\boldsymbol{X} = \sum_{m=0}^{M-1} \boldsymbol{X}_m \tag{18}$$

Each of the sub-blocks is then passed through an N-point IFFT block to obtain the corresponding PTS given by:

$$\boldsymbol{x}_m = IFFT\{\boldsymbol{X}_m\}, \qquad m = 0,1, \dots, M-1 \tag{19}$$

Let the number of allowed phase factors be W. So the phase factors can be expressed as:

$$b_w = e^{j\theta_w}, w = 0,1,..,W-1 \tag{20}$$

Generally the values used for phase factors are either [1,-1] or [1, +j, -j, -1]. It has been proved that these sets of phase factors produce acceptable values of PAPR [4].

Generally the first sub-block is left as it is, and rest is rotated. The modified OFDM symbol is:

$$\widetilde{\boldsymbol{x}} = \sum_{m=0}^{M-1} b^{(m)} \boldsymbol{x}_m \tag{21}$$

The optimum OFDM symbol to be transmitted is expressed as [5]:

$$\widetilde{\boldsymbol{x}}_{opt} = \min_{0 \le c \le C-1} \frac{\max_{0 \le k \le NL-1} |\widetilde{\boldsymbol{x}}_{k,c}|}{E[|\widetilde{\boldsymbol{x}}_{k,c}|]} \tag{22}$$

2.2 Advantages and Disadvantages

Like any other technique or algorithm, the PTS technique has a number of advantages as well as drawbacks or disadvantages. The advantages that have been pointed out by the authors of the original technique are described in the following sections. They have also pointed out the possible disadvantage of the technique. A detailed analysis of the drawback of the technique has been presented in the later sections. The further research work conducted on PTS technique has drawn the feed from the drawbacks of the technique.

2.2.1 Advantages of PTS Technique

The most important and significant advantages of the technique are listed and described below [4], [5]:

- ***Distortion less technique***: The technique introduces no distortion in the signal during the processing. Hence the BER performance of the OFDM system is not affected.
- ***Works with arbitrary number of sub-carriers***: As the technique is not dependent on the number of sub-carriers and the complexity of the technique is not

significantly affected by the number of sub-carriers, hence any number of sub-carriers can be used. Higher number of sub-carriers promises better data rates. So the technique provides the flexibility to work with any number of sub-carriers as per requirement.

- ***Works with any modulation***: The technique imposes no restriction on the type of modulation required. It will work equally well with BPSK or QPSK or any higher order modulation.
- ***Flexible approach***: The technique puts no restriction on number of sub-carriers or type of modulation, has a number of independent parameter such as number of sub-blocks and number and values of allowed phase factors. So it is very flexible and can be adapted as per requirement and modified as per need.
- ***PAPR reduction performance***: The most important advantage of the technique is that, it gives a very good PAPR reduction performance. The authors have proved that it gives a better performance than SLM technique [6].

2.2.2 Disadvantages of PTS Technique

The multiple advantages of the technique can be availed at the cost of certain drawbacks. They are as discussed below [4], [5]:

- ***High Computational Complexity***: The major disadvantage of the technique is the very high computational complexity incurred due to the multiple numbers of IFFT blocks and the multiple iterations to generate large number of candidate signals. Even if the technique offers a number of advantages and a very good PAPR reduction performance, but still the complexity can hold back the implementation of the technique in real systems.
- ***Loss in data-rates***: The information of the phase rotation of the sub-blocks is embedded in the OFDM symbol to be transmitted as side-information. This side-

information may cause a significant loss in data-rates if it is significant in comparison to the actual data being transmitted. This extra redundancy can be reduced by using large number of sub-carriers and less number of sub-blocks, e.g. N=1024, M=8.

2.3 Varied PTS Implementations

The high computational complexity of the PTS technique has been an incentive to the immense research work conducted to modify the technique such that the complexity is reduced to an acceptable limit. Some of the modified PTS techniques are described in this section. The main objective of these works has been to reduce the computational complexity yet maintain the PAPR reduction performance as the original technique.

- D. S. Jayalath and C. Tellambura have reduced the number of candidate signals in the year 2000 in their paper "*Adaptive PTS approach for reduction of peak-to-average power ratio of OFDM signal*," thus reducing the complexity. The search for the optimum candidate signal has been stopped when the PAPR falls below a pre-defined threshold value. The choice of the threshold value has been done according to the system in consideration [7].
- Xiao Yue, Lei Xia, Wen Qingsong and Li Shaoqian have used the correlation among the candidate signals to reduce the complexity in their paper "*A class of Low Complexity PTS Techniques for PAPR Reduction in OFDM Systems*" published in 2007.The technique has also focused on reducing the computational complexity for each candidate signal rather than reducing the number of candidate signals [8].
- PooriaVarahram, Wisam F. Al-Azzo, BorhanuddinMohd. Ali have used dummy signals in their paper "*A Low Complexity Partial Transmit Sequence Scheme by Use of Dummy Signals for PAPR Reduction in OFDM Systems*" published in 2010 to reduce the

complexity. The number of IFFT blocks have been reduced to half as that required in original PTS and the PAPR performance has been better too [9].

- Lingyin Wang and Ju Liu have proposed two low complexity phase computation methods in their paper "*PAPR Reduction of OFDM Signals by PTS with Grouping and Recursive Phase Weighting Methods*" published in 2011. These two phase weighting methods reduce the extensive complexity incurred due to exhaustive search of the optimum phase factors [10].
- Jun Hou, JianhuaGe and Jing Li have proposed a low complexity PTS technique in their paper "*Peak-to-Average Power Ratio Reduction of OFDM Signals Using PTS Scheme with Low Computational Complexity*" where they have utilized the correlation among the candidate signals to reduce the complexity. The novel ideas introduced by them included 'basis vector of the phase factors' and the complexity is significantly reduced and the PAPR reduction performance is maintained as per the original PTS [11].
- Sheng-Ju Ku, Chin-Liang Wang and Chiuan-Hsu Chen have introduced the concept of cost function which is the summation of the power of the time-domain samples in each sub-block in their paper "*A Reduced-Complexity PTS-Based PAPR Reduction Scheme for OFDM Systems*". Setting a threshold for the cost function, the process of finding out the most optimum phase factor has been optimized and the complexity has been reduced manifolds [12].
- Haibo Li, Tao Jiang and Yang Zhou are the most recent contributors to the betterment of PTS technique. Their paper "*A Novel Subblock Linear Combination Scheme for Peak-to-Average Power Ratio Reduction in OFDM Systems*" has removed the concept of candidate signal and has used an optimization technique through feedback for

finding out the most optimum phase factors. The complexity has been reduced manifold and the PAPR reduction performance has been improved as well [13].

Similar work has been conducted by several other researchers and the complexity has been reduced to very low values but at the cost of reduced PAPR reduction performance. A separate line of study has been existent which deals with the reduction of side-information and hence take care of the loss in data rates. The current work does not indulge into the reduction of side-information and hence those works has been safely excluded from the scope of study.

3

SINGLE IFFT BLOCK PTS TECHNIQUE

This chapter describes in details, the novel way of implementation of Partial Transmit Sequence Technique which resolves the major disadvantage of original PTS technique. The approach to the design of the new method has been discussed. The difference of the new approach with the techniques discussed in Chapter 2 has also been discussed in this chapter. The novel technique uses a single IFFT block and hence is referred to as Single IFFT block PTS. The algorithm to the technique has been discussed aided by mathematical equations. A block diagram has been presented to illustrate the algorithm and hence make the understanding more convenient.

Later on in this chapter, the simulation results have been presented in the form of graphical representations. An analysis of the results in terms of PAPR reduction performance has been done and it has been compared with that of original PTS technique and OFDM transmission without any PAPR reduction technique involved. The computational complexity of the new algorithm has been analyzed and compared to justify the claim of the new technique to reduce the complexity manifolds.

Finally the probable drawbacks of the technique have been discussed at the end of this chapter, with reference to the original PTS technique. An analysis of the throughput time of the algorithm has been provided and has been compared in respect to the original PTS technique. This has been concluded by the possible remedies to amend the drawbacks.

3.1 Single IFFT block PTS: Design Approach

The formation of the partial transmit sequences is accomplished using multiple IFFT blocks for each of the sub-blocks in the original PTS technique. These IFFT blocks itself have a complexity of $N*\log_2 N$ where N is the number of sub-carriers. When multiple numbers of such IFFT blocks are used, the complexity is increased manifolds. The process of formation of candidate signals also contributes significantly to the complexity. The entire process needed to generate one candidate signal is repeated W^{M-1} number of times and hence the overall complexity is increased.

The design approach has thus been concentrated on two major factors:

1. Reducing the number of IFFT blocks
2. Reducing the number of candidate signals

The number of IFFT blocks has been reduced to unity in the proposed technique. The algorithm has thus been modified to perform the entire process using only one IFFT block. The concept of candidate signal has been eliminated. Choice of optimum phase factors has been based on combination of a PTS with the PTSs preceding it. Effect of PTSs generated after a certain PTS has not been taken into consideration while deciding upon the optimum phase factor. As a result, the complexity due to multiple IFFT blocks and repetition of the same process to generate large number of candidate signals has been reduced immensely.

However it has been verified mathematically, that the proposed technique keeps the basic principle of original PTS technique intact. There is no loss in data-rates as the IFFT block being used will perform N-point IFFT. The proposed technique generates an OFDM symbol which is mathematically similar to that generated by the original PTS technique.

The approach to find the optimum phase factor has been altered to accommodate only one IFFT block in the system.

3.1.1 Single IFFT block PTS: Unique features

The proposed technique has a number of features which makes it different from the earlier works conducted in the same area. The technique does not need a predefined threshold value to reduce the number of candidate signals [6]. Hence the dependency of the performance of the technique on the choice of the threshold is removed. Mathematical complicacy has been avoided by keeping the mathematical principle same. The reduction in the number of IFFT blocks is from M to 1, unlike a reduction by half [7]. This reduces the complexity even further. The optimization of the phase factor has been done in the same way as original PTS does. Added complexity due to extra logic and computation is avoided [13]. Also the basic principle of PTS is maintained; hence the PAPR reduction performance is not degraded. In fact the simulation results prove that the PAPR reduction performance is improved by the proposed technique. The choice of the phase factor has been done by simply checking with the preceding PTSs. Thus the PAPR is reduced in every step an OFDM symbol is built. Hence the performance is better. The most important feature of the proposed technique which makes it different from earlier techniques is that, only one IFFT block has been used and the concept of candidate signal has been removed.

3.2 Single IFFT block PTS: Algorithm

The principle of the original PTS technique is to divide the incoming parallel block of data into sub-blocks; perform IFFT on each of these sub-blocks to generate partial transmit sequences; rotate the PTSs by a pre-defined phase factor and sum up the rotated PTSs in a manner such that the overall PAPR value of this particular OFDM block reduced to an acceptable limit. This process is repeated for W^{M-1} times using different combinations of phase factors and the candidate signal with the minimum PAPR is chosen as the OFDM symbol to be transmitted.

This technique is modified to incorporate only one IFFT block in place of multiple ones and replace the parallel processing with serial processing. Figure 3-1 illustrates the Single IFFT block PTS.

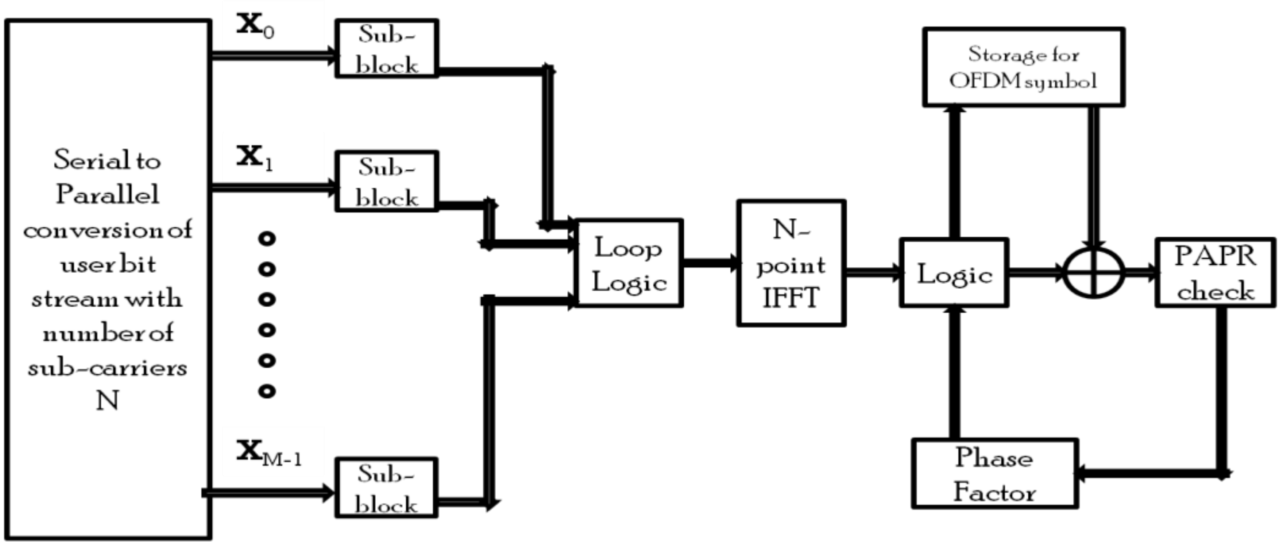


FIGURE 3-1: BLOCK DIAGRAM FOR SINGLE IFFT BLOCK PTS

The steps to the algorithm are as listed below:

- The incoming serial data stream is converted to parallel data blocks. The number of elements in the parallel data-block is N, where N is the number of sub-carriers.
- The entire parallel data-block is divided into M number of sub-blocks similar to the sub-block division method in original PTS described in Chapter 2.
- The "Loop Logic" blocks controls the serial execution of the process. In the first iteration, IFFT of the first sub-block is obtained. This gives the first PTS. The "Logic" block decides that if this is the first PTS, then it is stored as it is, that is to say, without any phase rotation, in the "Storage for OFDM symbol". After this is accomplished, the next iteration starts.

- For the second iteration, the second sub-block is converted to PTS by using the IFFT block. The "Logic" block knows that this is not the first PTS and a new loop is initiated. For the first iteration of the second loop, the 2nd PTS is rotated by the first phase factor and added with the stored OFDM symbol (that is the 1st PTS in this case). The PAPR of this combination is computed and held temporarily for comparison.
- The second iteration of the inner loop ensues, when the 2nd PTS is rotated by next phase factor and added to the 1st PTS; PAPR of this combination is computed and if it is less than the first value of the PAPR, then this phase factor is taken to be the optimum.
- This process continues for all the allowed phase factors until the combination of the 1st PTS and phase rotated 2nd PTS has minimum possible PAPR value.
- Once this has been accomplished, the 3rd sub-block is pulled into the iteration. The process continues until all the sub-blocks have been rotated and added to obtain an OFDM symbol with minimum PAPR.

Thus the new algorithm uses only **one** IFFT block and performs the process in a serial manner. The choice of optimum phase factor is done based on the PAPR value of the combination of a PTS and its preceding phase rotated PTSs. The OFDM symbol that is obtained has the lowest possible PAPR value, depending on the phase factor values being used.

3.2.1 Mathematical Analysis

Let the incoming serial stream of data be represented as X. If the number of sub-carriers be N, then let the parallel block of data obtained after serial to parallel conversion be represented as:

$$\boldsymbol{X} = [X_0, X_1, \dots, X_{N-1}]$$

If the number of sub-blocks be M, the parallel data block **X** is divided such that at least $\lfloor N/M \rfloor$ elements in each sub-block will be non-zero, as discussed in Chapter 2. So the sub-blocks can be expressed as $\mathbf{X}_m$ where:

$$\boldsymbol{X} = \sum_{m=0}^{M-1} \boldsymbol{X}_m \tag{23}$$

Each of the sub-blocks is then passed through an N-point IFFT block to obtain the corresponding PTS given by:

$$\boldsymbol{x}_m = IFFT\{\boldsymbol{X}_m\}, \qquad m = 0,1,\dots,M-1 \tag{24}$$

Let the number of allowed phase factors be W. So the phase factors can be expressed as:

$$b_w = e^{j\theta_w}, w = 0,1,..,W-1 \tag{25}$$

The OFDM symbol formed after the $(m+2)^{th}$ iteration when m = [0, M-1] by choosing the optimum phase factor for each PTS can be hence expressed as:

$$\widehat{\boldsymbol{x}}_m = \min_{0 \le w \le W-1} \left(\frac{\max_{0 \le k \le N-1} \left| x_k b_w^{(m)} + \hat{x}_{m-1} \right|}{E\left[\left| x_k b_w^{(m)} + \hat{x}_{m-1} \right|\right]} \right) \tag{26}$$

3.3 Computational Complexity Analysis

The proposed technique has been designed keeping in mind the objective to reduce the computational complexity which is a major drawback of the original PTS technique. To emphasize on the fact that the new technique has a considerably reduced computational complexity in comparison to the original PTS, it is necessary to analyze both the techniques to see the operations that contribute significantly to the computational complexity.

The major operations in both the techniques that contribute to computational complexity are as listed below:

- N-point IFFT
- Vector Addition of arrays of size [Nx1]

- Phase rotation of arrays of size [Nx1]
- PAPR calculation of partially formed OFDM symbol of size [Nx1]
- Comparison of PAPR values to obtain the minimum

Simple mathematical calculations have been done for both the techniques to find out the number of times these operations have to be performed. The values are enlisted in the following Table 3-1.

TABLE 3-1: COMPARISON OF COMPLEXITY OF STANDARD PTS AND SINGLE IFFT BLOCK PTS

Process	Original PTS	Single IFFT block PTS
N-point IFFT	MW^{M-1}	M
N-point Vector Addition	MW^{M-1}	W(M-1)
Phase factor multiplication	$M(W^{M-1}-1)$	W(M-1)
PAPR calculation	W^{M-1}	W(M-1)
PAPR value Comparison	$W^{M-1}-1$	W(M-1)

To quantify the reduction in complexity, the values have been calculated assuming N=64, M=4 and W=4. The values are enlisted below in Table 3-2:

TABLE 3-2: COMPARISON OF COMPLEXITY OF STANDARD PTS AND SINGLE IFFT BLOCK PTS: EXAMPLE

Process	Original PTS	Single IFFT block PTS
N-point IFFT	256	4
N-point Vector Addition	256	12
Phase factor multiplication	252	12
PAPR calculation	64	12
PAPR value Comparison	63	12

The values from Table 3-2 clearly indicates that the complexity of the Single IFFT block PTS is reduced to 6% of the computational complexity of the original PTS. Thus the proposed technique addresses a major drawback of an otherwise highly efficient method to reduce PAPR values in OFDM transmission.

3.4 Single IFFT block PTS: Receiver

The design of the receiver for OFDM with original PTS technique has been done by the inventors of PTS technique, Müller and Huber themselves. The basic principle to the design of the receiver is to counteract the changes that were incorporated in the transmitter while reducing the PAPR values of the OFDM signal. Based on the design approach, the receiver for the Single IFFT block PTS has been done mathematically and then simulated.

To formulate the reception of Single IFFT block PTS, the mathematical analysis of the transmitter is required. From equation (21), the phase rotated m^{th} PTS can be represented as:

$$\widetilde{\boldsymbol{x}}_m = \boldsymbol{x}_m b^{(m)} \quad \textbf{(27)}$$

Or we can expand it as:

$$\widetilde{\boldsymbol{x}}_m = \sum_{n=1}^{N} \sum_{k=1}^{N} X_{m,k} e^{j2\pi\frac{kn}{N}} b^{(m)} \quad \textbf{(28)}$$

So when all the phase rotated PTSs are added, the final OFDM symbol can be expressed as:

$$\widetilde{\boldsymbol{x}} = \sum_{m=1}^{M} \widetilde{\boldsymbol{x}}_m$$

or we can expand it as:

$$\widetilde{\boldsymbol{x}} = \sum_{n=1}^{N} \sum_{k=1}^{N} \left(\sum_{m=1}^{M} X_{m,k} b^{(m)} \right) e^{j2\pi\frac{kn}{N}} \quad \textbf{(29)}$$

Equation (33) clearly depicts that the data being transmitted is IFFT of each sub-block data multiplied by the corresponding phase factor.

The receiver is hence designed to perform the following two operations:

- Recover the side-information that conveys the phase factor values
- Perform FFT and then inverse the effect of the phases for each sub-block

From equation (33), it is evident that if the FFT of $\widetilde{\boldsymbol{x}}$is performed, the data that is recovered is:

$$\tilde{y} = FFT\{\widetilde{\boldsymbol{x}}\}$$

$$\tilde{y} = \sum_{m=1}^{M} \boldsymbol{X}_m b^{(m)} \quad \textbf{(30)}$$

Hence by using the side information, and by dividing $\tilde{y}$ into appropriate sub-blocks, the actual data can be recovered. However it is noteworthy that any loss or error in side information can lead to heavily erroneous decoding of data in such type of receiver.

The Single IFFT block PTS technique has maintained the mathematical structure of original PTS intact and hence the reception is exactly the same for the modified PTS. Here also the side information will be used to remove the additional phase introduced in each of the PTS after performing FFT on the received signal. Thus it is evident that any loss or error in side information will result in loss of information during decoding.

The receiver can thus be represented in the following Figure 3-2:

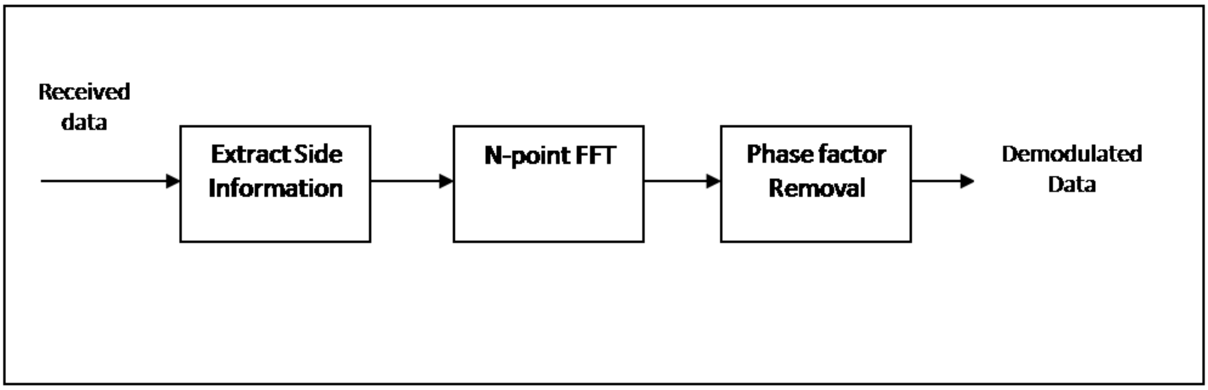


FIGURE 3-2: SCHEMATIC BLOCK DIAGRAM FOR THE RECEPTION OF OFDM WITH PTS TECHNIQUE

3.5 Simulation Results and Discussions

The proposed algorithm has been simulated in MATLAB R2012a on a CPU of 2 GB RAM working at a processor speed of 2.33 GHz. The different values of the parameters considered are tabulated below in Table3-3:

TABLE3-3: VALUES OF PARAMETERS USED FOR SIMULATION

Parameter Name	Values Used
Number of sub-carriers (N)	32 and 64
Number of sub-blocks (M)	4 and 8
Number of allowed phase-factors (W)	2 and 4

Different combinations of these parameters have been used to obtain the CCDF of the Single IFFT block PTS and compare it with that of original PTS and OFDM without any PAPR reduction technique.

It has been observed from the Figure 3-3, Figure 3-4, Figure 3-5 and Figure 3-6, that there is a significant improvement in PAPR reduction for the Single IFFT blocks PTS in comparison to the original PTS. This improvement can be quantified as 2-4 dB for different combinations of parameters and has the maximum value of 4 dB when 64 sub-carriers have been used along with 4 sub-blocks and 4 phase factors. So it is expected that if the values of N, M and W are increased the performance will improve further. Also in comparison to the simulation of OFDM without any PAPR reduction technique, the improvement is quantified to be 6-7 dB.

The results are illustrated through the following figures:

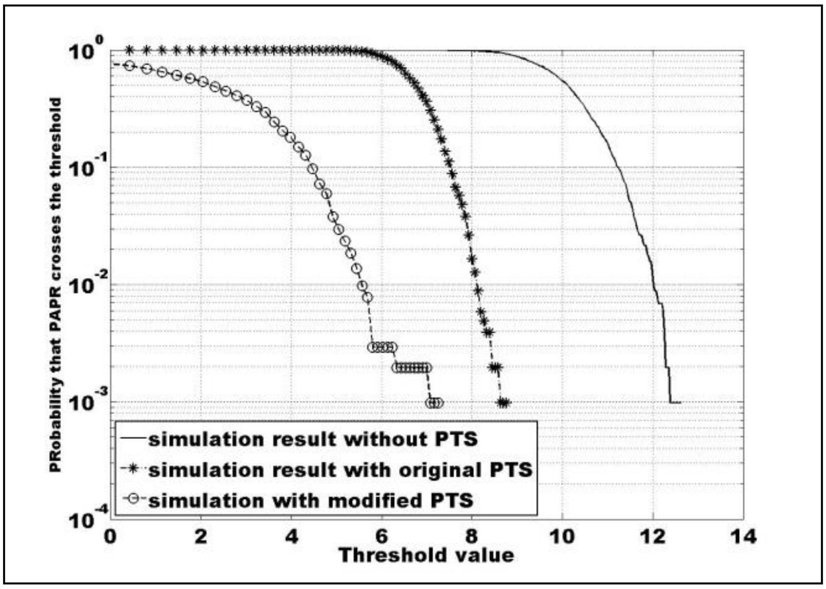


FIGURE 3-3: CCDF OF PAPR WITH N=32, L=2 AND M=4 FOR OFDM WITHOUT PTS, OFDM WITH PTS TECHNIQUE AND OFDM WITH SINGLE IFFT BLOCK PTS TECHNIQUE

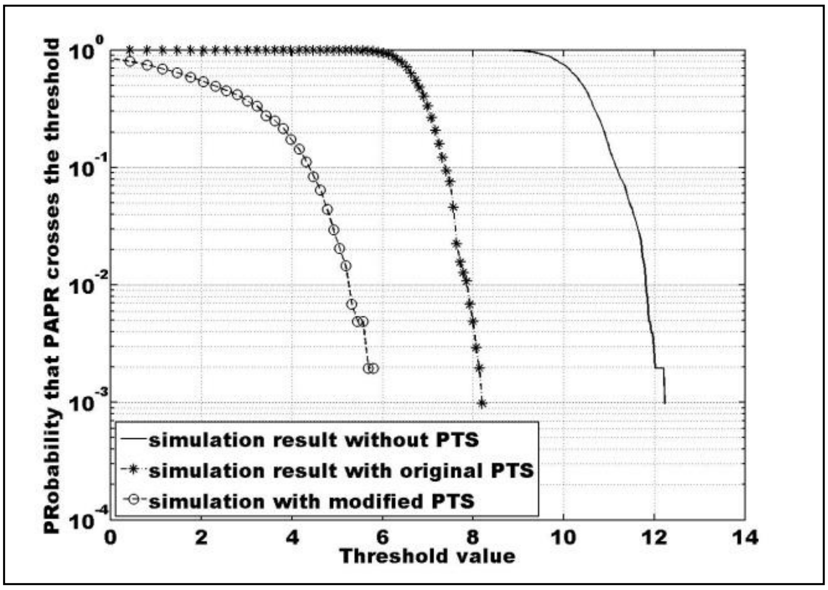


FIGURE 3-4: CCDF OF PAPR WITH N=64, L=2 AND M=4 FOR OFDM WITHOUT PTS, OFDM WITH PTS TECHNIQUE AND OFDM WITH SINGLE IFFT BLOCK PTS TECHNIQUE

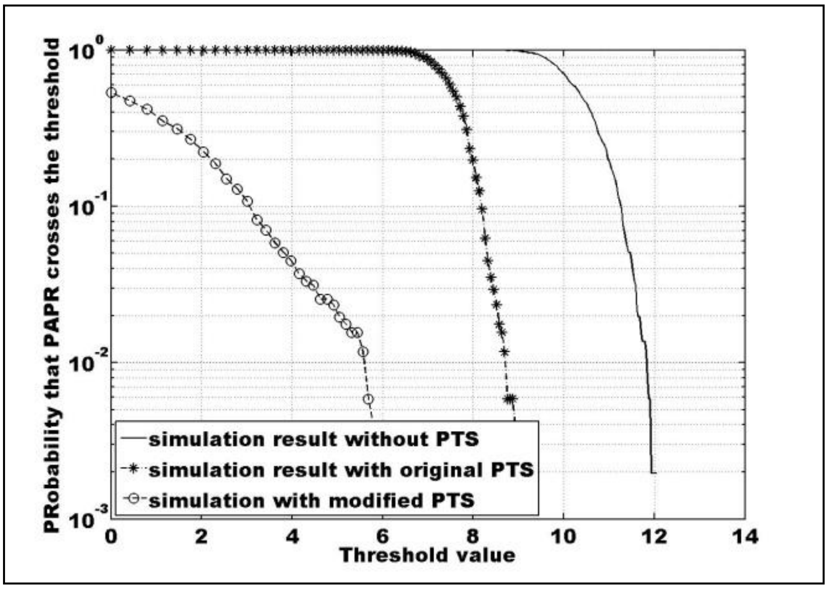


FIGURE 3-5: CCDF OF PAPR WITH N=64, L=2 AND M=8 FOR OFDM WITHOUT PTS, OFDM WITH PTS TECHNIQUE AND OFDM WITH SINGLE IFFT BLOCK PTS TECHNIQUE

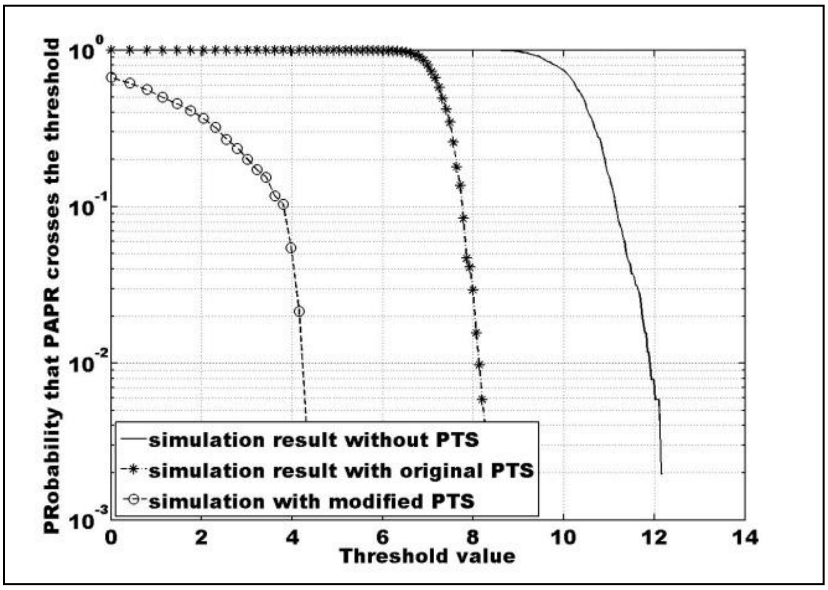


FIGURE 3-6: CCDF OF PAPR WITH N=64, L=4 AND M=4 FOR OFDM WITHOUT PTS, OFDM WITH PTS TECHNIQUE AND OFDM WITH SINGLE IFFT BLOCK PTS TECHNIQUE

3.5.1 Monte Carlo Simulation for Error Rate calculation

Once the transmitter and the receiver are designed and implemented for a communication system, the best way to measure the performance of both of them is by simulating a channel and noting the error rate while the signal is transmitted through the channel. An efficient way to do this is by Monte Carlo simulation.

Monte Carlo simulation is used to obtain a statistical analysis of any technique or system. The system or the technique is made to operate for repeated number of times and large amount of data is collected over each iteration. Finally a statistical analysis such as a graph is plotted to study the performance of the system or the technique.

Hence using Monte Carlo simulation, the transmitter and receiver of OFDM with Single IFFT block PTS are judged on the basis of symbol error rate. The simulation steps are as discussed below:

1. Data generated in the transmitter is converted to binary form to be transmitted over the channel.
2. Additive white Gaussian noise is used to corrupt the signal while passing through a channel.
3. The received data is decoded as per the receiver design.
4. Received data is compared with transmitted data to find out the number of errors.
5. This process is repeated for large values of data transmitted.
6. The steps 1-5 are repeated for different SNR values varying from 1 dB to 20 dB and each time the probability of symbol error is calculated.
7. Finally a plot is obtained for symbol error rate versus different SNR values.

Two scenarios are considered for obtaining the SER vs SNR graphs. In the first scenario, the side-information is not corrupted by the channel. It is assumed that the side-information is received as it is on the receiver side.

The SER vs SNR graphs that were obtained for the first scenario is shown below:

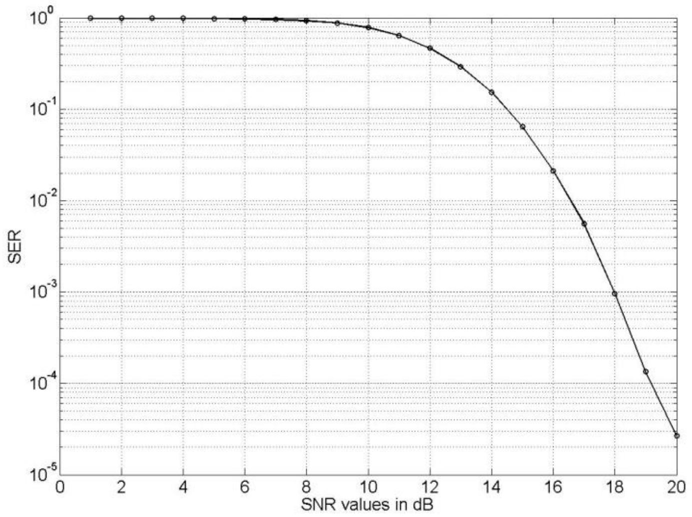


FIGURE 3-7: SER VS SNR GRAPH FOR 2^{17}SYMBOLS TRANSMITTED

To check if the symbol error rate performance of Single IFFT block PTS in first scenario is at par with OFDM without any PAPR reduction technique, the complete transmitter receiver and channel model was designed for simple OFDM. The steps 1-7 were repeated for the second model and both the plots of SER vs SNR were compared. The simulation result obtained is illustrated in the following figure:

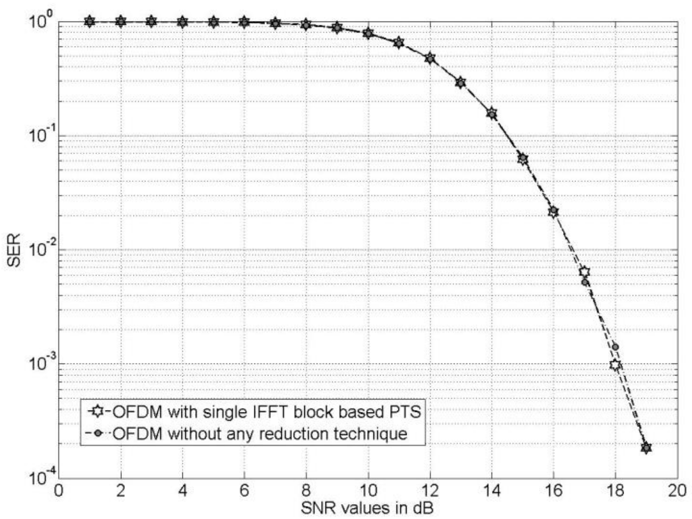


FIGURE 3-8: COMPARISON OF SER VS SNR GRAPHS FOR OFDM WITHOUT ANY PAPR REDUCTION TECHNIQUES AND WITH SINGLE IFFT BLOCK PTS TECHNIQUE

The second scenario is where the side-information has also been corrupted by the AWGN channel and hence a certain drop in SER performance is expected. The SER vs

SNR graphs of the two scenarios, i.e. PTS technique without side-information being corrupted and PTS technique with side-information being corrupted, are compared in the following graphs.

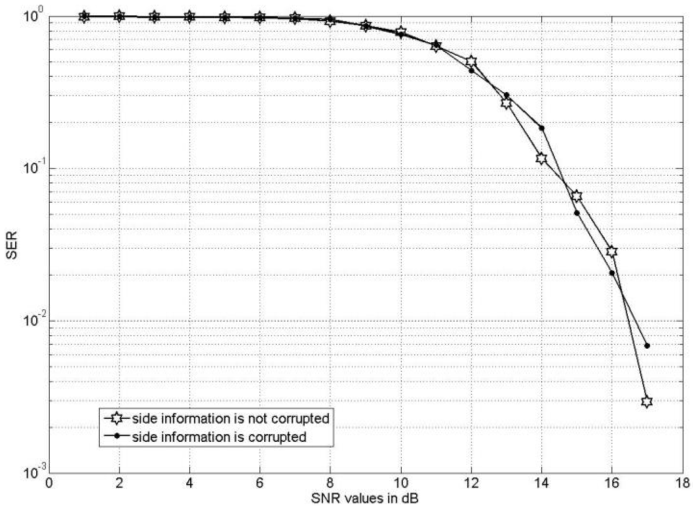


FIGURE 3-9: SER VS SNR GRAPHS FOR SINGLE IFFT BLOCK PTS OFDM FOR THE SCENARIOS WHERE SIDE-INFORMATION IS CORRUPTED AND IS NOT CORRUPTED: 2^{10} SYMBOLS USED

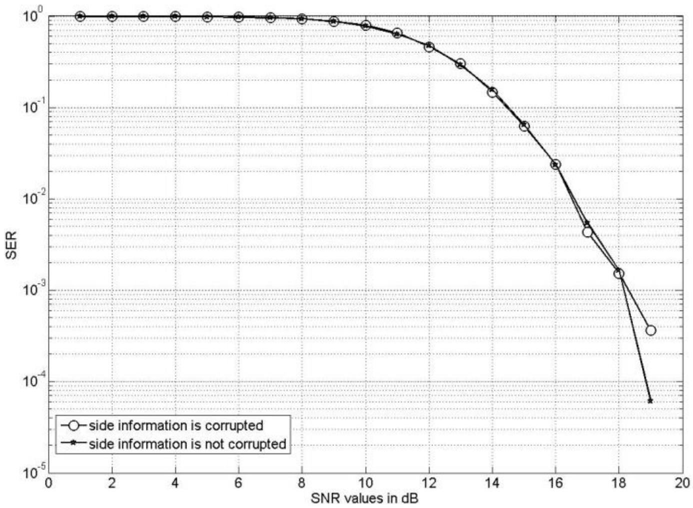


FIGURE 3-10: SER VS SNR GRAPHS FOR SINGLE IFFT BLOCK PTS OFDM FOR THE SCENARIOS WHERE SIDE-INFORMATION IS CORRUPTED AND IS NOT CORRUPTED: 2^{14} SYMBOLS USED

Figure 3-7 clearly shows that when the side-information is not corrupted, there is a remarkable improvement in SER performance after 8 dB and an acceptable SER of 10^{-4} is achieved at higher SNR values.

Figure 3-8 gives a clear comparison between the SER performances of OFDM without any PAPR reduction technique and OFDM with the proposed technique and side-information being kept out of the effect of the channel. It is evident that both have similar performance throughout except at few places. However the slight variation is not always positive and hence over the entire range gets approximately nullified.

Figure 3-9 and Figure 3-10 give the comparison of the SER performances of OFDM with the proposed technique where side-information is corrupted in one scenario and is not corrupted in the other scenario. The graphs show that there is a slight degradation in SER performance at higher SNR values. But this can be improved by better channel coding of the side-information.

Hence it is proved that the Single IFFT block PTS technique does not affect the error rate performance very heavily of the OFDM system. This again establishes the fact that in comparison to original PTS technique, the modified technique fares better; the error rate performance is maintained, the PAPR reduction capability is improved and above that the computational complexity is reduced. An exhaustive comparison has been done to claim the same by considering different scenarios where side-information may or may not affect the overall SER performance.

3.6 Single IFFT block PTS: Implementation Issues

The proposed technique of Single IFFT block PTS has been effective in reducing the computational complexity of the original method and has also delivered a better performance in terms of PAPR reduction. However, like any practical technique, this technique is also not without any drawback.

Since the entire process is being done in a sequential manner, the obvious drawback is the throughput time. Any serial system is always slower than parallel systems but has a lower complexity. The throughput time of Single IFFT block PTS can be analyzed by assigning each of the operations a pre-defined time variable and then finding out the total time required for a complete iteration.

Let the time variables be defined as enlisted in the following table:

TABLE 3-4: TIME VARIABLES FOR DIFFERENT PROCESSES

Process	Time Variable
N-point IFFT	t_{ifft}
N-point vector addition	t_{add}
Phase rotation	t_{phase}
PAPR computation	t_{PAPR}
PAPR comparison	t_{cmpr}

For original PTS, one OFDM symbol will be generated in t_{sym} given by:

$$t_{sym} = t_{ifft} + t_{phase} + t_{add} + t_{PAPR} \tag{31}$$

So the process will be completed to generate the OFDM symbol with minimum PAPR in t_{pts} given by:

$$t_{pts} = t_{sym} * W^{M-1} + t_{cmpr} * (W^{M-1} - 1) \tag{32}$$

Evaluating in a similar way for Single IFFT block PTS, the time required for a partial OFDM symbol to be formed with the minimum possible PAPR for that particular combination of PTSs is t_{part} given by:

$$t_{part} = t_{ifft} + W * t_{phase} + W * t_{add} + W * t_{PAPR} + (W - 1) * t_{cmpr} \tag{33}$$

So the total time required for generating an OFDM symbol using Single IFFT block PTS is $t_{single\_ifft\_pts}$ given by:

$$t_{single\_ifft\_pts} = (M - 1) * t_{part} + t_{ifft} \tag{34}$$

So the time required for both the techniques are compared in the following table:

TABLE 3-5: TOTAL TIME REQUIRED FOR GENERATION OF MINIMUM PAPR OFDM

Original PTS	Single IFFT block PTS
$(t_{ifft} + t_{phase} + t_{add} + t_{PAPR}) * W^{M-1} + t_{cmpr} * (W^{M-1} - 1)$	$(M-1) * (t_{ifft} + W * t_{phase} + W * t_{add} + W * t_{PAPR} + (W-1) * t_{cmpr}) + t_{ifft}$

So the number of times different time variables are repeated for both the techniques are enlisted below:

TABLE 3-6: NUMBER OF REPETITION OF TIME VARIABLES

Time Variable	Number of repetition in Original PTS	Number of repetition in Single IFFT block PTS
t_{ifft}	W^{M-1}	M
t_{add}	W^{M-1}	W*(M-1)
t_{phase}	W^{M-1}	W*(M-1)
t_{PAPR}	W^{M-1}	W*(M-1)
t_{cmpr}	$W^{M-1}-1$	(W-1)*(M-1)

Substituting the values of W and M as W=4 and M=4, the number of times each time variable appears for both the techniques are shown in the following table:

TABLE 3-7: NUMBER OF REPETITION OF TIME VARIABLES – AN EXAMPLE

Time Variable	Number of repetition in Original PTS	Number of repetition in Single IFFT block PTS
t_{ifft}	64	4
t_{add}	64	12
t_{phase}	64	12
t_{PAPR}	64	12
t_{cmpr}	63	9

Table 3-7 clearly shows the total time required by Single IFFT block PTS is much less than that of original PTS even if the technique is serial. However, when compared with some of the modified PTS techniques, where the number of candidate signals is reduced significantly, the time required by Single IFFT block PTS will be more than that of the modified techniques.

3.6.1 Pipelining technique to reduce through put time

The through put time can be reduced by pipelining the system taking care that there is no un-wanted overlap between the processing of two subsequent PTSs.

Pipelining is possible in two stages. The first loop which consists of sub-block division and then subsequent PTS generation through IFFT can be pipelined for each sub-block. The second loop consisting of the phase factor multiplication, addition of phase rotated PTSs and then subsequent PAPR computation and choosing the most optimum phase factor can be pipelined. It has to be taken care that, one PTS has to wait until the second loop is complete for the previous PTS.

There can be two cases of reduced timing by pipelining the first loop, depending on whether the time required by IFFT is more or the second loop is more.

- ***Case 1***: Assuming that the time required by IFFT is more than the time required by the entire second loop, then for the generation of a complete OFDM symbol, the time required will be:

$$t_{pipelined\_case1} = \left(W * t_{phase} + W * t_{add} + W * t_{PAPR} + (W-1) * t_{cmpr} \right) + M * t_{ifft} \quad \textbf{(35)}$$

- ***Case 2***: Assuming that the time required by the second loop is more than that required by IFFT then the time required for complete OFDM symbol generation will be:

$$t_{pipelined\_case2} = (M-1) * \left(W * t_{phase} + W * t_{add} + W * t_{PAPR} + (W-1) * t_{cmpr} \right) + 2 * t_{ifft} \quad \textbf{(36)}$$

In case of pipelining the second loop, assuming that the time required for all the processes are same, we can write:

$$t_{phase} = t_{add} = t_{PAPR} = t_{cmpr} = t \quad \textbf{(37)}$$

Thus the time required for completion of the second loop for one PTS will be:

$$t_{2nd\_loop} = (2W-1) * t \quad \textbf{(38)}$$

in place of $(4W-1) * t$. Hence pipelining can improve the throughput time considerably.

4

HARDWARE IMPLEMENTATION OF SINGLE IFFT BLOCK PTS USING C6713DSK

The novel algorithm developed to counteract the drawback of high computational complexity of PTS technique has been tested for its workability through simulation, as presented in Chapter 3. It has also been shown that the computational complexity is reduced by a large magnitude and the PAPR reduction performance has also been improved by significant amount. However the feasibility of actual implementation of this technique needs to be tested to certify that the technique will work in real time or at least near to real time. Any algorithm that can be simulated does not guarantee that it can be emulated. So emulation is necessary for any technique to be full-proof.

The algorithm involves important signal processing elements such as IFFT and phase rotation. Hence a fast digital signal processor (DSP) and a corresponding DSP Starter Kit (DSK) is the best suited emulator to test the algorithm initially. A DSK titled C6713DSK provided with a high speed floating point processor TMS320C6713 from TI was selected for the purpose, depending on availability as well. The algorithm was emulated using this DSK and the reduction in PAPR in comparison to a normal OFDM signal was calculated from actual measurements.

The chapter gives a brief description of TMS320C6713 and C6713DSK and the software used to program this DSK. The implementation of the algorithm in the software and subsequent execution in the DSK has been described, aided by photographs of the setup. The results and calculations from the results obtained have been discussed in the last sections of the chapter. Finally an analysis of the time complexity of the technique has been done to establish the feasibility of real world implementation.

4.1 C6713DSK with TMS320C6713

DSP Starter kits (DSK) are complete boards with on-board processors, memories, emulators, JTAGs, USB connection, audio jacks, LEDs and binary switches which can be used for speedy development of high precision applications in the domain of DSP. Texas Instrument along with Spectrum Digital has developed a number of such DSKs. There are different families of DSK, depending on the processors being used. The DSKs can be fixed point or floating point in nature and hence are selected as per the requirement.

The DSK in consideration is a low-cost development platform designed to speed the development of high precision applications based on TI´s TMS320C6000 floating point DSP generation. The DSK features the TMS320C6713 DSP, a 225 MHz device delivering up to 1800 million instructions per second (MIPs) and 1350 MFLOPS. This DSP generation is designed for applications that require high precision accuracy. The C6713 is based on the TMS320C6000 DSP platform designed to needs of high-performing high-precision applications such as pro-audio, medical and diagnostic. Other hardware features of the TMS320C6713 DSK board include:

- Embedded JTAG support via USB

- High-quality 24-bit stereo codec
- Four 3.5mm audio jacks for microphone, line in, speaker and line out
- 512K words of Flash and 16 MB SDRAM
- Expansion port connector for plug-in modules
- On-board standard IEEE JTAG interface
- +5V universal power supply

The kit uses USB communications for true plug-and-play functionality. The DSK also hosts an AIC23 codec which helps in conversion of incoming analog signal to digital data and vice-versa. The input lines are multiplexed; the multiplexing can be controlled through programming. So input can be taken from both the lines if required or only one line can be used. The output lines are however not multiplexed and bear the same output signal. The codec has a range of sampling frequencies varying from 8 KHz to 96 KHz. The sampling frequency can be selected as per the signals in consideration. Similarly there is a range of word length that can be used to represent the digital data varying from 16 bits to 32 bits. Signal processing techniques that require very high precision are thus very effectively implemented in this DSK. The image of the DSK used for the actual measurements is shown in the following figure along with the schematic block diagram of the internal structure of the board.

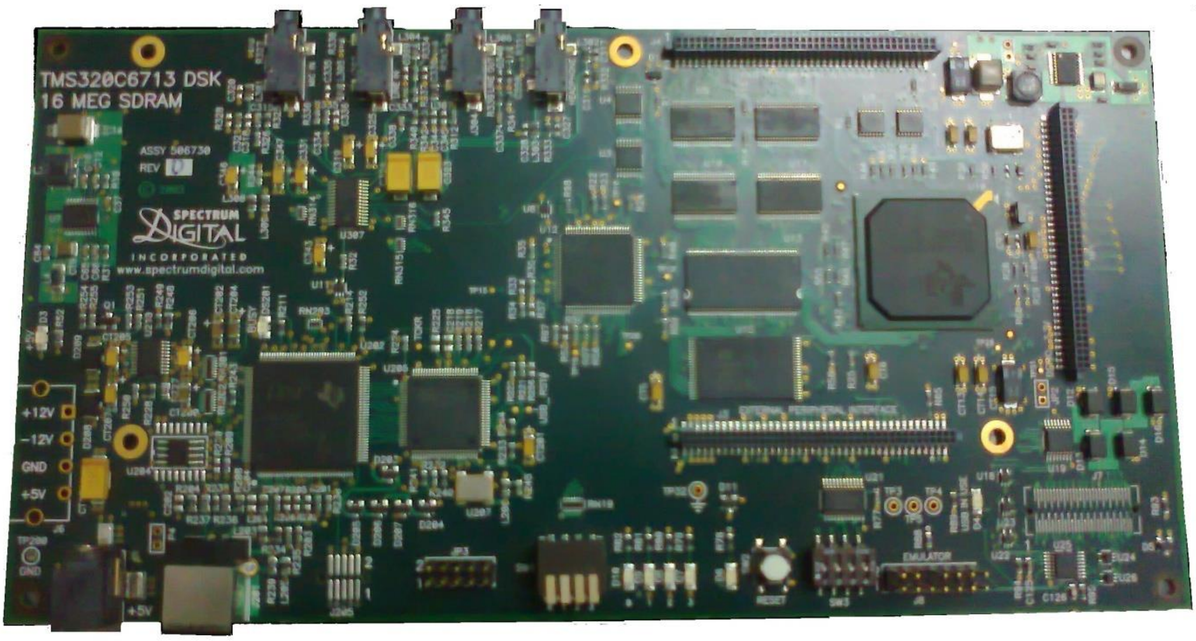


FIGURE 4-1: C6713DSK

The DSK can be programmed using a Cross-compiler which runs on the CPU but compiles and executes programs on the DSP of the board, when the DSK is connected through USB connection. The most common cross-compiler used to program the DSK is Code Composer Studio. There are two ways to work on CCS. The first technique is to write the algorithms directly in C or C++ using the libraries made for C6713DSK. The second technique is to build a MATLAB-Simulink model and then using linking files, the Simulink model can be converted to C code compatible with CCS and the target. In both the cases, the C code is compiled by CCS and then executed in the DSP through the USB connection.

It is noteworthy that only till version 3.3, CCS was compatible with MATLAB. CCS v4 and above do not support the automatic conversion of Simulink model to C code through tlc files. As a matter of fact the most convenient pair of CCS and MATLAB-Simulink to work with is CCS v3.1/3.3 and MATLAB R2007b. In this combination, a Simulink model, if built with the correct targets and blocks from Real Time Workshop toolbox, can be built into C code, compiled and executed through CCS onto DSP by a single command.

Hence for convenience and to avoid any error due to mismatch of software versions, the Single IFFT block PTS technique has been implemented using CCS v3.3 and MATLAB-Simulink R2007b onto C6713DSK. The details of the procedures are discussed in the following sections.

4.2 Experimental setup and Simulink Model

The Simulink model was built for the algorithm using Embedded MATLAB function blocks. The blocks were built through MATLAB coding. The schematic diagram for the Simulink model is as shown in Figure 4-2:

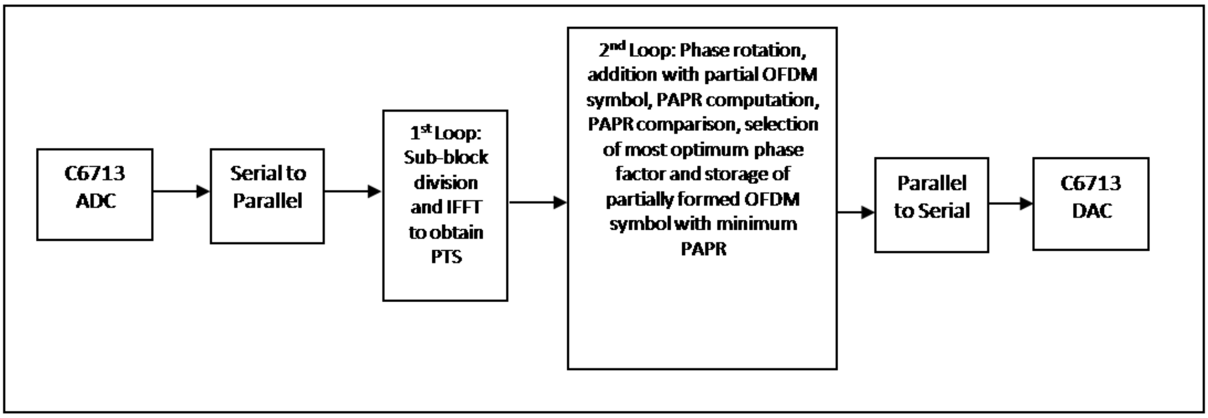


FIGURE 4-2: SCHEMATIC BLOCK DIAGRAM FOR SIMULINK MODEL

The input was taken from a function generator through the “Line In” jack of the DSK board. The ADC block in the Simulink model represented the digital data obtained after digitization of the signal by the on-board ADC. The samples were then processed as per the algorithm implemented and the final samples were converted back to an analog signal by the on-board DAC. This output signal was observed in a Digital Storage Oscilloscope. The PAPR of OFDM signals with and without Single IFFT block PTS were calculated and then compared graphically. The experimental setup is shown in the following figure while the obtained results are discussed in the following sections.

FIGURE 4-3: EXPERIMENTAL SETUP

FIGURE 4-4: DSK IN USE DURING EXPERIMENT

The sampling frequency used for the experiment is 32 KHz and a word length of 20 bits was used. The input was taken from the Line-In and output was taken from Line-Out. The results obtained have been discussed and analyzed in details in the following sections.

4.3 Results and Discussions

The experimental setup discussed in Section 4.2has been used to generate OFDM signal with and without Single IFFT block PTS technique to reduce OFDM. The OFDM signal output was observed on Digital Storage Oscilloscope. The following figures show some of the snapshots of the continuous signal being output to the DSO.

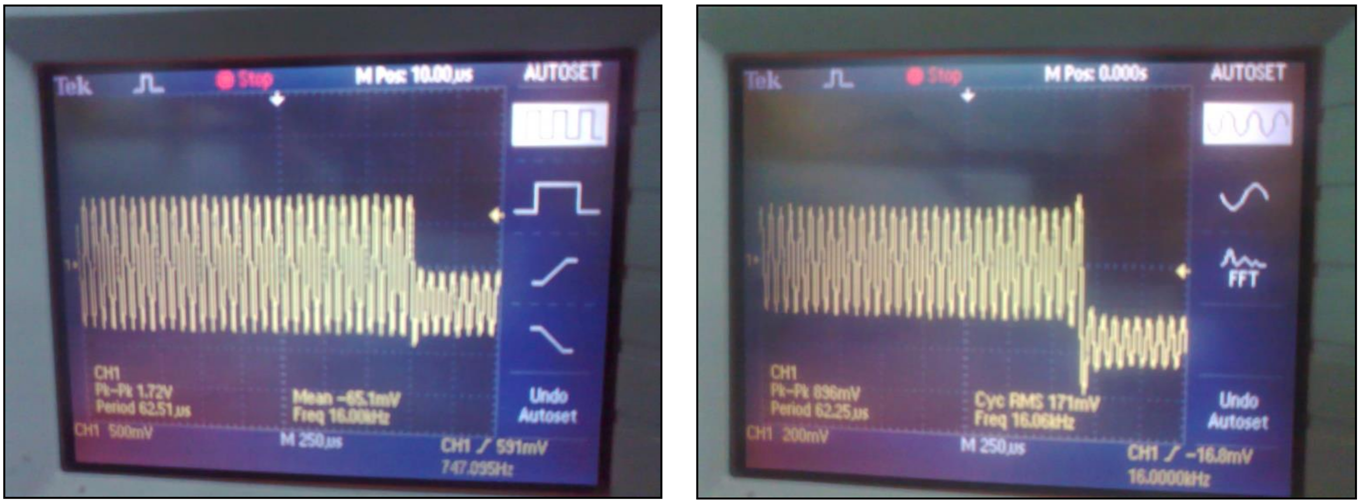


FIGURE 4-5: OFDM SIGNAL ON DSO

The PAPR calculation was done in the following steps:

1. Note down the instantaneous peak-to-peak value of amplitude
2. Note down the instantaneous mean value at the same instant
3. Divide the peak-to-peak value by 2 to obtain the instantaneous maximum value
4. Square the instantaneous maximum value
5. Square the mean value
6. Divide square of instantaneous maximum value by square of mean value
7. Obtain the value of the ratio in dB – this gives the PAPR value

The values are noted down for a large number of instants and then they are plotted graphically for better comparison and analysis.

The PAPR values obtained for OFDM with and without Single IFFT block PTS have been calculated and plotted in the following Figure 4-6. The difference in the values shows the improvement of PAPR reduction by the proposed technique. On an average there is an improvement of 8.81 dB in PAPR values in comparison to OFDM without any PAPR reduction technique. This value is in compliance with the results obtained in simulation in Chapter 3.

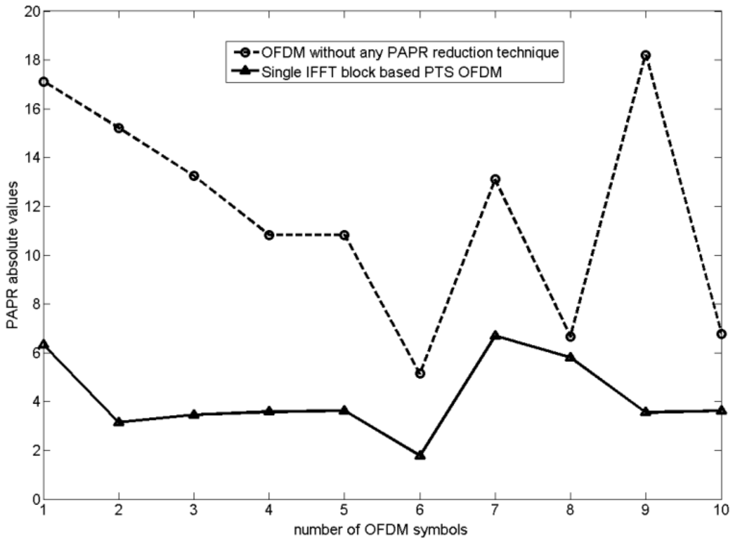


FIGURE 4-6: PAPR VALUES FOR OFDM WITH AND WITHOUT SINGLE IFFT BLOCK PTS OBTAINED BY EMULATION ON C6713DSK

The values obtained by simulating the Simulink model using data similar to that being provided to the DSK has been compared with those obtained after emulation on the DSK.

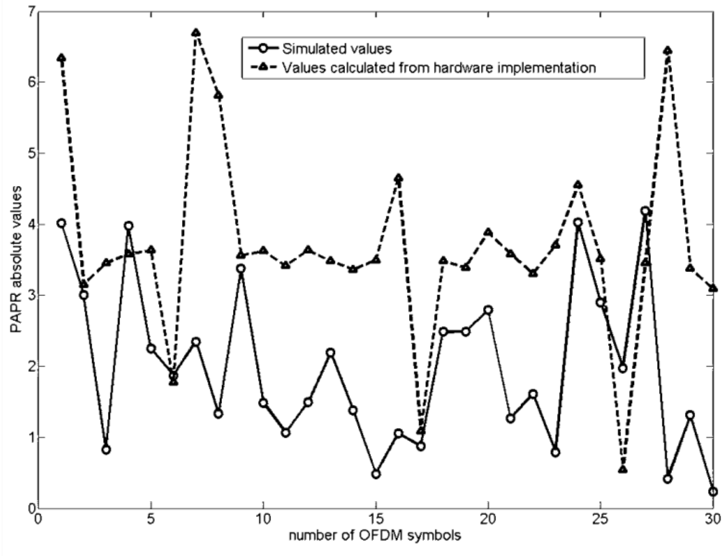


FIGURE 4-7: COMPARISON OF PAPR VALUES OBTAINED BY SIMULATION AND EMULATION WITH SIMILAR INPUT DATA

The graphical representation shows that the values agree to an acceptable limit and hence proves that the technique works very well in real hardware with a memory and speed constraint.

4.4 Time complexity Analysis of DSP Implementation

The total number of clock cycles required for obtaining the output after the 1st sample enters is 24458408. The clock frequency of the emulator is 225 MHz. Hence the time required for generation of one OFDM symbol is approximately 0.108704 seconds.

Each of the OFDM symbol is generated after processing a combination of $N * m$ samples where N is the number of sub-carriers and m is the word length of the actual data. For the experiment, the value of N is 64 and value for m is 100. Hence for 6400 samples to be processed, the time taken is 0.108 seconds approximately. Now the codec being used is AIC23 with a sampling frequency of 32 KHz. So the time required for generation of 6400 samples is 0.2 seconds. Hence every set of samples enter the first loop after every 0.2 seconds and the time required for total processing of the set of samples through 1st as well 2nd loop is 0.108 seconds. Hence effectively, there is no loss of samples in between due to waiting time. This shows that the technique has an acceptable time complexity and holds the feasibility to be implemented in real time system.

It can be further calculated that samples are not lost up to a sampling frequency of 48 KHz. As theoretically sampling frequency of 48 KHz is appropriate for signals of 24 KHz frequency content, so the maximum frequency of the input signal will be 24 KHz.

The sampling frequencies are fixed in C6713DSK; hence the data rates that can be accommodated will take up fixed values. However a generic calculation can be done to find out the data rates possible for the system.

It is clear from the initial calculations that 6400 samples can be handled after 0.109 seconds. So the minimum time required for 6400 samples to be generated is 0.109 seconds. Hence time required for one sample will be 17.03 microseconds. If more time is required, the operating frequency will decrease accordingly. And if less time is required, then a buffer is required to hold the generated samples so that no sample is lost. Considering each sample is generated in 17.03 microseconds and then the corresponding sampling frequency will be 58.7156 KHz. If each sample is represented by 8 bits, then the permissible data rate will be 469 Kbps. The time complexity analysis establishes the fact the system can be implemented in hardware and with certain improvements and improvisations can be made to work for real time system.

5

CONCLUSION

The most important technology in use in the modern wireless industry is undoubtedly OFDM. All the existing standards are using OFDM in its pure form or a variant form such as OFDMA, MIMO-OFDM or MC-CDMA. Hence all the systems have to face the basic drawback of high PAPR incurred in normal OFDM. Several techniques have been implemented to check the value of PAPR from crossing a certain acceptable limit. PTS technique has been one of those techniques which have delivered a very good PAPR reduction performance but at the cost of high computational complexity. Multiple modifications of PTS exist which try to reduce the complexity and yet maintain the PAPR reduction performance. The final objective is to formulate such a technique that would use the principle of PTS and reduce PAPR effectively and yet can be efficiently deployed in real time systems.

Single IFFT block PTS has been a new step towards the same objective. The new algorithm has been proposed after a thorough analysis of the significant modifications of PTS technique. The technique has a very low computational complexity and delivers a performance significantly better than PTS technique. The hardware requirement has been reduced significantly by cutting down multiple IFFT blocks to one, only with the addition of smaller loop control logical blocks which do not contribute to complexity as much as the IFFT blocks. The performance has been effectively better as PAPR has been reduced in every step of formation of the OFDM symbol from the PTSs.

The technique has been simulated and the results have been obtained in the form of CCDF graphs for OFDM without any PAPR reduction technique, OFDM with original PTS and with the new technique. A comparison has been done among the three and it has been clearly visualized that the new technique gives 2-4 dB betterment in PAPR reduction performance compared to original PTS and a significant 6-7 dB improvement from OFDM without any reduction technique. The complexity of original PTS and the new technique has also been compared and it has been proved by calculation that complexity is reduced manifolds.

Having established the claims of the technique, it has been emulated in C6713DSK to test the feasibility of hardware implementation of the same. The experiment proves the fact through calculations and observation, that the technique is very well suited for hardware implementation with minor betterments in throughput time.

But any technique would have to pay a cost for achieving certain objectives. The Single IFFT block PTS technique is a serial process hence the throughput time might be more than some of the modified PTS techniques, as discussed in earlier chapters. However it has been proved that the through put time for the new technique is better than that of original PTS. The concept of pipelining has been introduced for the technique which can improve the throughput time. The process of pipelining has been discussed theoretically and the possible time required has also been calculated theoretically. Thus the scope of betterment lies in the pipelining of the technique.

Any communication system, be it a transmitter or a receiver is required to be tested for the error rate performance, once the signal is passed over some channel. Henceforth, the receiver of OFDM with PTS technique is discussed and it has been shown that the same receiver can be used for OFDM with Single IFFT block PTS. The transmitter and the receiver are then modeled into a complete communication system using an AWGN channel. Symbol error rate has been calculated and plotted for varying SNR of the channel. A comparison has also been done among the SER versus SNR plots of OFDM without any PAPR reduction technique and OFDM with the proposed technique. Two scenarios have been considered; one scenario assumes that the side information is not corrupted while the other scenario assumes that the side information is corrupted by the AWGN channel. It has been established that the proposed technique does not degrade the SER performance of the OFDM system significantly and hence is distortion-less.

It is noteworthy that OFDM is generally employed in the downlink of most of the communication systems. This is because the OFDM transmitter requires heavy processing and it is cost and power efficient to implement the signal processing techniques in the BTS rather than the handsets. Hence all the PAPR reduction techniques are implemented in the processor of BTS. It is expected that the receiver has minimum complexity and thus PTS reception is an area that can be worked upon to make it less complex. This provides for a scope of future betterment on the receiver of OFDM with PTS without affecting the error rate performance.

5.1 Future Work

The future works that can be conducted on the technique are deduced from the drawbacks of the technique. As discussed in Chapter 3, the major problem with Single IFFT block PTS is the higher through put time due to the serial nature of the technique. And as discussed, there is ample scope of work by pipelining the technique.

The feasibility of hardware implementation has been tested using DSP hardware. Thus the scope lies in implementation of the technique in FPGA. If the technique can be implemented and executed well in FPGA, the technique will be proved in all aspects to be efficient. The pipelining can be done in FPGA as well and would add to the scope of future work.

There are options to apply the technique to some of the variants of OFDM, such as OFDMA and MIMO-OFDM and hence check the universality and flexibility of the technique. The final objective would be to make the technique online so that actual transmission systems can deploy the technique without any loss in data rates or much added complexity.

Moreover as discussed in Chapter 3, the receiver of PTS is complex in nature. Since it is desirable that the handsets being used at the user end host minimum complexity in the reception mechanism, so the complexity of the reception technique can be worked upon to be reduced to an acceptable limit, yet maintaining the good error rate performance PTS provides.

DISSEMINATION:

Gupta, I. ; Patra, S.K. , "**Single IFFT block based reduced complexity Partial Transmit Sequence technique for PAPR reduction in OFDM**", *IEEE International Conf. on Communications, Devices and Intelligent Systems 2012*, Jadavpur University, Kolkata, pp, 53-56, Dec 2012

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